USE OF WSP CONCEPTS IN RISK MITIGATION OF DISTRIBUTION SYSTEMS AT UNDER CAPACITY OPERATION - A CASE STUDY ON KANDY SOUTH WATER DISTRIBUTION SYSTEM

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Degree of Master of Science

Department of Civil Engineering

University of Moratuwa
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October 2015

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Dissertation is submitted in partial fulfillment of the requirements for the degree

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DECLARATION OF THE CANDIDATE AND SUPERVISOR

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Use of Water Safety Plan concepts in risk mitigation of distribution systems at under capacity operation – A case study on Kandy South Water Distribution System

ABSTRACT

A Water Safety Plan is one of the most effective ways of ensuring that a water supply is safe and reliable for human consumption and that it meets the health and demand based standards and other regulatory requirements. WSP is based on a comprehensive risk assessment and risk management approach to all the steps in a water supply chain from source to consumer. Recently introduced WSP for distribution systems is a new concept to NWSDB. However, the NWSDB, being the authority directly responsible for treatment and delivery of drinking water to the consumer, has commenced implementation of the WSP approach to the distribution system as a first step.

Numerous studies were found in literature for assessing the formation and behavior of disinfection by products, residual chlorine and other hydraulic parameters in water distribution systems. Yet the studies related to WSP for distribution system approach were not frequently found.

The risk assessment of an under capacity operating system is carried out throughout this study and the recommendations were made to mitigate those in future. Maligathenna scheme, which is a sub-scheme coming under Kandy South Region was analyzed in detail. The main parameters concerned were Trihalomethane, Residual Chlorine, Pressure, Water Age, Total Organic Carbon, Turbidity and Conductivity.

Water quality parameters were tested at site or in the laboratory. A hydraulic model was built using Water GEMs software to determine the hydraulic parameters such as pressure, water age. A special water quality model was developed to assess the performance of the distribution network and predict the parameter values for the future.

General conclusions along with the specific recommendations were made based on the results and observations met throughout the study. WSP hazard identification and assessment approach is followed throughout the study. Some alarming findings were listed with respect to TTHM and RCl. However clear and significant relationships among the parameters could not be found. Most of the recommendations which were made at the end of the study are expected to be implemented either in design stage or during operation and maintenance period.

Key words: Water safety plan, Water quality parameters, Hydraulic parameters, Pipe distribution system, Risk assessment

ACKNOWLEDGEMENTS

First my special gratitude goes to Senior Professor Mrs. Niranjanie Ratnayake, the research supervisor, for her precious guidance and kind support with patience and encouragement provided throughout the research.

In addition my sincere thanks are also for the Co-supervisor Dr.S.K.Weragoda, Chief Engineer (NWSDB) who has initialized this research topic and for the guidance, encouragement and critical comments throughout the research period.

Further my grateful thanks are expressed to Dr. Jagath Manatunga, the Course Coordinator of Master of Science in Environmental Engineering and Management Degree for giving the opportunity to undergo through the dissertation and for knowledge gained. Further thanks go to Dr. Mahesh Jayaweera and all the academic and non-academic staff of the Department of Civil Engineering, University of Moratuwa for their kind help given to make this piece of work a success.

I would like to extend my grateful appreciation to Eng.C.R.Perera, Deputy General Manager(NWSDB), Eng.(Mrs.)M.K.Bandara, Deputy General Manager (NWSDB), Eng.K.W.Premasiri, Deputy General Manager(NWSDB), Eng.B.U.J.Perera, Chief Engineer (NWSDB) who were my superiors at work for providing this opportunity to continue my higher studies.

My appreciation is incomplete if I do not mention the enormous support and help extended by Mr.Gayan Amarasekara, National Research Council and University of Peradeniya for water quality testing work. Further I should convey my gratitude to Greater Kandy Laboratory staff, Mr.R.G.S.Pushpakumara, OIC, Kandy South Water Treatment Plant and his staff and Kandy RSC staff for their for their support during various parts of the study.

Above all, I wish to thank my wife Hasanthi, son Randeera, mother, father and sister for their never-ending moral support and encouragement throughout the study period without which I will never be able to complete this study.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation		Description
TTHM	-	Total Trihalomethane
RCl	-	Residual Chlorine
TOC	-	Total Organic Carbon
DBP	-	Disinfection by Products
OIC	-	Officer in Charge
NWSDB	-	National Water Supply and Drainage Board
DI	-	Ductile Iron
GI	-	Galvanized Iron
CT	-	Contact Time
SLS	-	Sri Lanka Standards
WHO	-	World Health Organization
WSP	-	Water Safety Plan
UV	-	Ultraviolet
WTP	-	Water Treatment Plant
DEM	-	Digital Elevation Model
SACDA	-	Supervisory Control And Data Acquisition
NRW	-	Non Revenue Water
WTP	-	Water Treatment Plant
O&M	-	Operation and Maintenance
USEPA	-	United States Environmental Protection Agency
NOM	-	Natural Organic Matter
DOC	-	Dissolved Organic Carbon
GIS	-	Geographical Information System

LIST OF APPENDICES

1. INTRODUCTION

Water is one of the most important substances on earth. All plants and animals must have water to survive. If there was no water there would be no life on earth. Water makes up more than two thirds of human body weight, and without water, we would die in few days. The human brain is made up of 95% water, blood is 82% and lungs 90%. A mere 2% drop in our body's water supply can trigger signs of dehydration.

In addition, it has been said that the water will probably be the next resource over which wars will be fought. This implies the importance of the potable water, which is about 0.009 % of the whole water in the planet. Water scarcity has being increased with the growth of global population and the industrial revolution. Industrial revolution led the above situation to a critical level. It polluted the water bodies, which have been used for drinking and other human activities. Consequently, providing enough access to safe drinking water has become one of the main challenges to any government especially with the changing trends influenced by climate change. This issue is particularly critical in developing nations when there are limited resources that would require the need of putting in place an efficient integrated water resource management policy and regulation.

1.1 Background to research

Hazardous agents, including microbial pathogens and chemical contaminants, that get access to drinking-water and distribution systems could affect the quality of the water and have an adverse impact on human health. In addition there are various hazardous events that could affect the water quality and the physical and hydraulic integrity of the distribution system, leading to water in distribution systems becoming contaminated or to supply being interrupted.

Control measures are barriers necessary for preventing or reducing significant water quality risks. They need to be developed, implemented and monitored for each hazardous event identified as significant in the risk assessment. In the context of the distribution system components, control measures are defined as those measures required in drinking-water distribution systems that directly affect the safety or aesthetics of drinking-water, either by preventing the occurrence of hazards or by inactivating, removing or reducing them to acceptable levels. Control measures can include a wide range of activities and processes. Such as preventive (and incorporated in design, planning and construction processes and renewal of infrastructure), treatment related (e.g. secondary disinfection), technical (e.g. operational and maintenance procedures) and behavioural (e.g. customer awareness programs).

Among the several initiatives taken to provide safe water to people all over the world by different agencies, Water Safety Plan (WSP) has become the latest concept which ensures the safety of drinking water through the use of a comprehensive risk assessment and risk management approach that encompasses all steps in water supply from catchment to consumer.

Water Safety Plan

The integrity of well managed distribution systems is one of the most important barriers that protect drinking-water from contamination. However, management of distribution systems often receives too little attention. Distribution systems can incorrectly be viewed as passive systems with the only requirement being to transport drinking-water from the outlets of treatment plants to consumers.

A WSP is the most effective way of ensuring that a water supply is safe and reliable for human consumption and that it meets the health and demand based standards and other regulatory requirements. It is based on a comprehensive risk assessment and risk management approach to all the steps in a water supply chain from catchment to consumer. (WHO manual on WSP)

WSPs implies that actions are required at all stages in the process of producing and distributing water in order to protect water quality and to ensure the water quantity. This includes source protection, treatment (when applied) through several different stages, prevention of contamination during distribution (piped or non-piped) and maintenance within households.

In the case of distribution systems, it is assumed that water is safe to drink at the point of entry, so the aim becomes to maintain safety by preventing contamination after treatment. In simple terms, this includes:

- Constructing systems with materials that will not leach hazardous chemicals into the drinking-water;
- Maintaining integrity to prevent the entry of external contaminants;
- Maintaining the supply of drinking-water to consumers;

- Maintaining conditions to minimize the growth of microbial pathogens (e.g. Legionella) and biofilms, scaling and accumulation of sediments.

  (DWI – A brief guide to drinking water safety plans October 2005)

According to the WSP approach following are the key steps in the methodology.

1. Assemble WSP team
2. Describe the water supply system
3. Identify hazards & hazardous events & assess risks
4. Determine & validate control measures, reassess & prioritize risks
5. Develop, implement and maintain an improvement/upgrade plan
6. Define monitoring of the control measures
7. Verify effectiveness of the WSP
8. Prepare management procedures
9. Develop supporting programs
10. Plan and carry out periodic review of the WSP
11. Revise the WSP following an incident
12. Enabling environment

Water safety plan is not yet implemented in Kandy South region distribution systems. Therefore there might be several unidentified and unquantified significant risks involved in the pipe distribution system. I wish to focus mainly on water quality issues related to RCl, THM, Turbidity, Conductivity and Total Organic Carbon. Apart from that, the impact on water quality by system hydraulic parameters (Pressure, Water Age) is also investigated and tried to find probable correlations with water quality parameters. Module 03 of water safety plan manual discusses about the hazards and hazardous events of a water distribution system. Module 04 discusses about the control measures to be implemented to avoid or mitigate the risks. These guidelines were followed to organize the research process and outline the final conclusions and recommendations.

1.2 Aims and objectives of the research

During the design stage of a water distribution system the standard practice is to carry out the designing work to cater the water demand and to maintain a satisfactory pressure at the customer’s point. The relationships between system hydraulic parameters and water quality parameters are not considered at any stage of design.

Design of water treatment plants are carried out to meet the standard drinking water quality parameter levels while being able to meet the consumer demand. Treatment techniques are basically meant to remove the turbidity of the raw water and disinfect with chlorine against possible pathogenic micro-organisms. Though a certain residual chlorine level (0.2mg/l) is to be maintained throughout the distribution system in order to prevent the recontamination within the distribution system, it was observed that some of the locations of distribution system are not having the specified RCl level. Proper investigations are not carried out to identify this situation and analyze the extent of this threat to customers.

Being the premier water utility agency in Sri Lanka, National Water Supply and Drainage Board currently operates around 300 water supply schemes island wide. All those schemes are having regular water quality monitoring programs, which monitors the common physical, chemical and micro-biological parameters at the designated sampling locations within the distribution system.

Literature shows that several disinfection by-products could be formed when chlorine is used as the disinfecting agent. Among numerous DBPs, THM is the most outstanding substance came across frequently which is supposed to be closely related with the organic compounds content of water. Though it is such a vital parameter to be tested in drinking water, it is not a parameter routinely checked by NWSDB because the necessary laboratory facilities are not available in most of the regions. Hence the public health is in a risk because the extent of the risk is unknown. Routine testing of THM is not a feasible option with the available resources, as such it is important to study the factors that lead to the formation and the behavior of THM in the distribution system in order to control the concentration within the acceptable limits. Both operational and design parameters need to be modified to achieve this.

Apart from RCl and THM, some other water quality parameters such as turbidity, total organic carbon and conductivity are also need to be analyzed and study the actual behavior and possible inter-relationships in order to have a clear understanding on the system to ensure the required drinking water quality.

The implementation of module 03 and 04 of WSP manual is an ideal approach to address these problems. Through that the potential hazards and hazardous events could be identified, their behavior could be analyzed and possible control measures could be proposed.

1.3 Scope of work and limitations

National water supply and drainage board currently operates in all most all the districts, divisional secretary areas in Sri Lanka. It serves more than 1.8 million connections in the country supplying water to more than 6 million people. I have selected my study area as the Maligathenna Water Supply Scheme in Kandy South region maintained under the Central Regional Support Center. It is one of the fifteen schemes fed by Meewathura Treatment Plant, having a total distribution length of around 60km and serving 3700 connections. Due to the time and resource limitations I have limited my scope of study to RCl, TTHM, Turbidity, TOC and Conductivity as water quality parameters and associated hazards. The testing of TTHM was not possible in most of laboratories of NWSDB, hence I had to get the Support from Greater Kandy Laboratory. The hydraulic parameters I wished to study are Water Age and Pressure. There were several barriers that I had to encounter when collecting field data on distribution network. I had to closely coordinate with OICs, technical officers and refer the available maps and design reports.

2. LITERATURE REVIEW

2.1 Introduction

2.1.1 Background to the literature review

This chapter presents a brief review of literature on issues related to supply of safe drinking water and an overview of the techniques used in disinfection such as, various disinfection methods, requirements for disinfection, advantages of chlorination over other modern techniques and the main disadvantage of using chlorine for disinfection – formation of Trihalomethane. Finally, it comes to the interest of this research, Water Safety Plan (WSP), the evolution of WSP approach and studies on the identification of relationships among the selected parameters so that measures can be incorporated into the water safety plans for the water supply scheme.

2.1.2 Waterborne diseases and epidemics

Many waterborne and water related diseases such as cholera, dysentery, typhoid, etc suddenly bloomed as outbreaks many times in the past. The phase of such epidemics had changed to a complex scenario with the pipe water supply in the middle of 19th century, which was led to spread cholera and typhoid in many countries. Figure 2.1 presents a few examples for the epidemics, taken place throughout in the history.

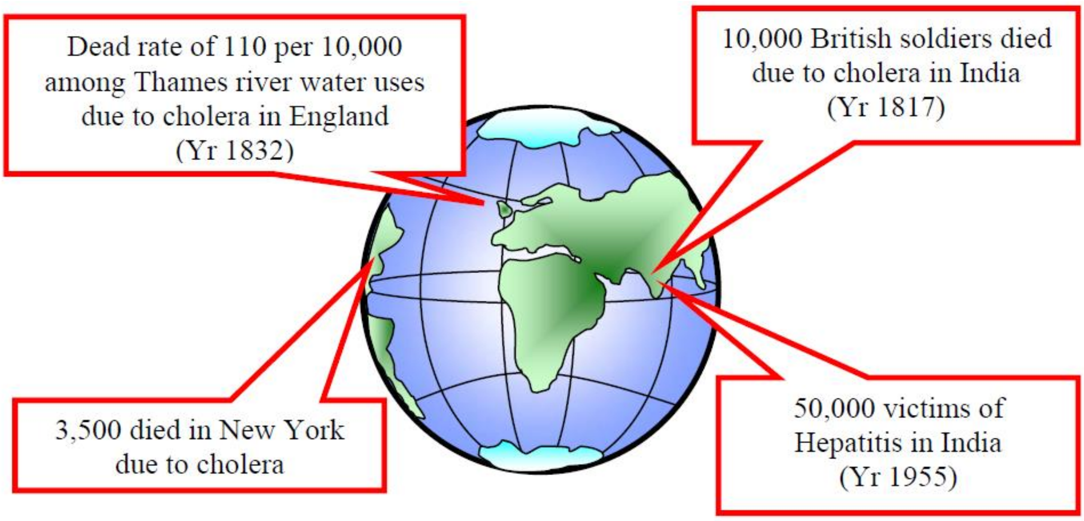


Figure 2.1: Epidemics of waterborne diseases (Okun, 1996)

One of the main diseases that caused huge damage to the human society is Cholera. Written history of cholera goes up to the early part of the 19th century. Dr. John Snow, physician of Queen Victoria, has made the first hypothesis as cholera is waterborne. In the 19th century, cholera became the world's first truly global disease in a series of epidemics. As an example, it had been recorded that about 10,000 imperial troops died due to cholera in India during 1817 and so far, no records were found on the deaths of the natives (Weragoda, 2005).

In 1832, during the first major recorded cholera epidemics in London, deaths from cholera ranged from about 10 per 10,000 to 110 per 10,000 among those who were using Thames River water. During the same time period, in New York City, an epidemic of waterborne cholera took the lives of more than 3,500 people (Okun, 1996).

Hepatitis is another waterborne disease, which had been raised as epidemics with the supply of pipe water. In New Delhi, more than 50,000 cases were reported about infectious hepatitis in 1955. It made the engineers to think again thoroughly about the selection of the water sources and importance of adequate treatment facilities (Okun, 1996). These all led to the invention of chlorinator in US in the early stage of 20th century.

2.1.3 Requirements for safe drinking water

The importance of safe drinking water has been emphasized in the above section of this chapter. But with the increasing demand for the potable water due to the rapid urbanization, access to the safe drinking water has been limited drastically in many countries. This made to think about various alternatives such as rainwater harvesting, ground water investigations, desalination of lagoon and sea water etc to bridge the gap between the demand and the availability of potable water.

In fact, rapid urbanization has polluted surface water significantly. It has become a challenge to water engineers, to produce new technologies which can cater such complex pollution levels in water bodies. Jolly et al., (1984) have listed out different kinds of pathogens, found in river water. Figure 2.2 presents some common bacteria, viruses and their relevant diseases. It is interesting to emphasize that almost all the pathogens are added to the water from human faeces. Therefore, the treated water has to be checked for them. The current common practice of doing this in most countries is by checking total and faecal coliforms in the water.

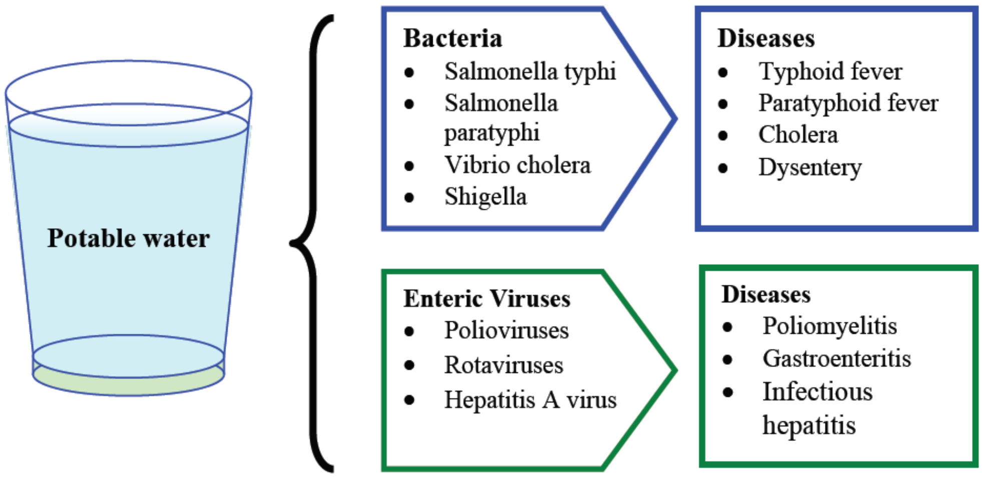


Figure 2.2: Common pathogens and relevant diseases that could be found in drinking water (Weragoda, 2005)

2.1.4 Water treatment technology and distribution networks

No single water treatment technology is effective in treating all water problems. Specific technologies are applied to meet specific needs, either individually or in combination. Water treatment facilities have to be designed to produce water, which is compatible with drinking water standards, using whatever the available water source, which has been selected to construct the intake of the treatment facility.

Water treatment plants are usually consisted of the unit operations such as screening, aeration, coagulation, flocculation, sedimentation and filtration. In addition to them, there are some chemicals, which are added at several places of the treatment process. Lime, which is added to correct pH prior to coagulation and flocculation, alum as a coagulant, polyelectrolyte as a coagulant aid, and many forms of chlorine as disinfectants are common examples for the chemicals.

Usually a water distribution system starts from the clear water and ends up at the consumer's water tap. Water distribution systems are basically constructed with DI, GI, PVC and/or PE pipes, water pumps, and water towers and/or ground reservoirs.

Design and construction of water treatment plant basically involves four steps (Qasim et al., 2000):

- The first step is the site selection;
- The second step involves development of a cost-effective process train to delineate the proper relationship of the various steps in the treatment plant;

- The third step involves sizing the individual treatment units and placing them in the available area to achieve proper sequence and hydraulics, to provide access for operation and maintenance of equipment, and to minimize the total space requirements;
- Finally, the connecting pipings are tied down with topography, process units, buildings, chemical and feed lines, roads and pumping needs.

2.2 Disinfection

Disinfection is the most important stage in the treatment of drinking water supplies, because it destroys or inactivates pathogenic organisms, which are responsible for waterborne diseases such as cholera, typhoid fever, and dysentery. Most of the pathogenic organisms found in water are bacteria, some water borne viruses are also known to be human pathogens. The common indicator organism, faecal coliform,is a very good indicator for viruses.

Most of the municipal water supply systems in the developing countries use chlorination as disinfection. As mentioned above, disinfection is used to safeguard consumers from both present and future pathogenic microbial infections. In order to ensure any future biological growth, the residual effect should be provided. Chlorination is the only disinfection technique which can produce such a residual effect to the treated water in the distribution system.

2.2.1 Disinfection modes

The mechanism of destruction of pathogenic organisms in disinfection depends to a large extent on the nature of the disinfectant and on type of organisms. Even though the actual mechanisms are not fully understood yet it appears that most disinfectants act destructively on cell protein: particularly by destroying enzyme systems that are critical and essential for microbiological life.

2.2.2 Importance of disinfection

Disinfection refers to the inactivation of pathogens. Factors, which influence successful disinfection are;

1. Time of contact
2. Temperature and chemical character of water
3. Kind and concentration of disinfectant

4. Kind and concentration of organisms to be destroyed
5. Concentration of organic matter

The disinfectant concentration and contact time (CT) are the prime factors in the inactivation of microorganisms. The product of the concentration and CT for a specified level of kill provides a useful term to compare disinfectants and factors affecting microbial inactivation. The CT values for each of the disinfectants are variable. The free species of chlorine are effective disinfectants and rapidly inactivate bacteria, viruses, and protozoan cysts at low concentrations.

Temperature influences the rate of microbial inactivation and the rate of disinfectant consuming side reactions. Extreme temperatures, which are outside the range of cardinal temperatures for the particular species, will have a direct disinfection effect. In addition temperature also affects the disinfection reaction rate, since it affects the diffusion rates of disinfectant through the cell walls.

The extent and rate of disinfection are influenced by the type and physiological state of the microorganism. In general, bacteria are more susceptible than viruses, which are more susceptible than protozoan cysts (White, 1972). In the case of bacteria, they are "stressed" by disinfection and because of that, those bacteria have to undergo a period of recovery before reaching their full reproductive potential and commencing rapid cell division (Jegatheesan et al., 2004). This can be further controlled by maintaining residual chlorine level in distribution systems.

Most micro-organisms are effectively killed by extreme pH conditions (pH<3 or >11). Relative resistance is observed in moderately basic or moderately acid (pH 4-10) solutions. Under these conditions, and in the presence of another disinfectant, however, pH may exert a marked effect on the reactivity of either the micro-organism or the disinfectant, or both.

2.2.3 Different chemicals and methods used in disinfection

The most economical method of disinfection for large scale use is chemical disinfection. Chlorine gas, also known as elemental chlorine, is a powerful oxidizing and disinfecting agent, which is the most popular technique of disinfection. In water treatment plants, chlorine gas is used mainly at two places, as pre and post chlorination. While chlorine gas remains the most commonly used water disinfectant, a number of chlorine and non-chlorine alternatives are used in water treatment technology. Sodium hypochlorite is a chemical compound used to add chlorine to water. It is transported and stored in solutions containing 5 to 20% chlorine. It can be generated on site but in many places it is transported to the treatment plants. Calcium hypochlorite is another chlorinating chemical. It is available in granular and tablet forms.

In addition to those, there are some chlorine related compounds like chloramines and chlorine dioxide, which are used as disinfectant in the water treatment plants. Chloramines are chemical compounds formed in the water by combining chlorine in a specific ratio with ammonia. Chlorine dioxide is a powerful disinfectant and oxidizer, generated on-site. Although it contains chlorine atoms, it disinfects through a different mechanism than chlorine.

With a long description of chlorine related chemical, it is better to discuss about other chemicals, which have been introduced with quite sophisticated technology. Ozonation and ultraviolet (UV) radiation are modern techniques, introduced to water treatment as disinfection methods. Ozone is a powerful oxidizing and disinfecting agent generated on-site by passing oxygen or dry air through a system of high voltage electrodes. UV is generated by special lamps.

Providing a proper disinfection system is one of the main priorities in planning and designing of WTPs. The disinfection system of a treatment facility has to be selected with a close consideration of the following factors:

- Be able to destroy pathogens at concentrations likely to occur in water and effective under normal environmental conditions:
- Compliance with federal, state, and local regulations;
- Reliability of disinfection system;
- Safe and easy shipping, storage and handling of disinfectants;
- Potential hazards to people and the environment from chemicals and equipment;
- Potential to form disinfection by-products;
- Affordability (considering capital investments and O&M costs).

No single disinfection method is suitable for all requirements. In fact, decisions for individual facilities are made locally, based on local water quality conditions, as well as community priorities and resources.

2.3 Chlorination

2.3.1 Introduction to Chlorination

Chlorine means “greenish yellow” in Greek. Scheele, who thought it contained oxygen, discovered chlorine in 1774. Davy, who insisted it was an element, named chlorine in 1810. Chlorine is a respiratory irritant. The gas irritates the mucus membranes and the liquid burns the skin. As little as 3.5 ppm can be detected as an odour, and 1000 ppm is likely to be fatal after a few deep breaths. In fact, chlorine was used as a war gas in 1915 (Chlorine, August 2004).

Chlorine is an element of the halogen family, but it is never found uncombined in nature because of its higher reactivity. It is estimated to account for 0.15% of the earth’s crust in the form of soluble chlorides, such as common salt (NaCl), carnallite (KMgCl3.6H2O), and sylvite (KCl). In nature, therefore, it exists only as the negative chloride ion with a valance of (–1).

Chlorine is commercially produced by anodic oxidation of NaCl aqueous solution.

$$2H_2O \quad + \quad 2NaCl \quad \Longleftrightarrow \quad H_2\uparrow + \quad 2NaOH \quad + Cl_2\uparrow$$

The Chlorine gas produced thus is purified by washing in sulphuric acid to remove water and liquid Cl_2 to remove chlorinated hydrocarbons and ferric chloride. This yields Cl_2 gas of >99.5% purity. The gas is liquefied at 25psi between 0-25 ^{0}F and charged in to steel cylinders or tanks. Pure Chlorine gas is not corrosive and can be stored in steel cylinders, but moisture renders Cl_2 highly corrosive to metals.

Chlorine could be hazardous in many ways.

- Toxicity of the gas
- Its high reactivity and dangers of fire and/or explosion
- Corrosion
- High pressure under which the gas is stored

Therefore every possible precaution should be taken in handling of Chlorine.

2.3.2 Chemistry of Chlorination

Chlorine gas is dissolved either in water directly (by a chlorinator) to form hypochlorous acid. Otherwise, chlorination can be done by mixing water with any other appropriate chemical mentioned in above section. This solution is then used as a disinfectant, and upon mixing with water, hypochlorous acid is formed, as in the first method.

When chlorine gas is dissolved in water, it hydrolyzes rapidly according to the following equation.

$$Cl_2 + H_2O \rightarrow H^+ + Cl^- + HOCl$$

The dissociation of Cl_2 in water H_3O^+, Cl^- and HOCl molecules are formed, is called disproportionation. Due to the high magnitude of the constant of disproportionation and rapid establishment of this equilibrium, free Cl_2 molecules are virtually absent in water of pH>3, and at Cl^- levels <1000mg/l. Hydrolysis of Chlorine reduces the pH in weakly buffered water. Further, Hypochlorous acid (HOCl) molecule is a stronger disinfectant than hypochlorite ion (OCl^-), and the relative distribution of these varies with pH.

Many investigators have studied the phenomenon of the hydrolysis of chlorine with water. It is one of the most significant chemical reactions to take place when chlorine gas is dissolved in an aqueous solution. The reaction rate of chlorine in water is very high and it requires only very few seconds for complete hydrolysis of Cl. The rate constant for this reaction is about 5 x 1014 indicating that reaction occurs at almost every collision of ions.

The chemistry of the reaction is of great practical significance. It can be seen from this equation that the concentration of HOCl depends on the total chlorine concentration and pH. Hyperchlorous acid is classified as a "weak" acid, which means that it tends to undergo partial dissociation as following:

$$HOCl \leftrightarrow H^+ + OCl^-$$

Therefore, one HOCl ion produces a hypochlorite ion and a hydrogen ion. The amount of hypochlorite ion becomes appreciable above pH 6, while molecular chlorine is nonexistent. When pH value of the chlorinated water is 7.5, 50% of the chlorine will remain as hypochlorous acid (HOCl) and 50% will be the hypochlorite ion OCl^{-1}. The higher the pH values the greater the concentration of OCl^{-1} ion. Therefore, pH value plays a significant role in this mechanism. It has been observed that a 50 % dissociation of hyperchlorous acid can be experienced when pH becomes 7.5 in aqueous media (Frateur et al., 1999).

Exactly the same phenomenon occurs when hypochlorite is used instead of gaseous chlorine. If, for example, common bleach (sodium hypochlorite) is used, it disperses in water as following:

$$NaOCl + H_2O \rightarrow HOCl + NaOH$$

In fact, NaOCl is one of the suitable chemicals, which can be used for chlorination in the laboratory.

It is well known that the amount and complexity of pollutants, reaching to surface water bodies, have been increased at an alarming rate during the recent past. This has created a direct effect to the reactions of chlorine in aqueous solutions. In general, it can be said that the factors presented in figure 2.3 are significant in their reactions with chlorine (Okun, 1996).

In general, Cl reacts with both natural and synthetic organic matters in the water. It has been observed that Cl usually reacts with natural organic matters, such as Humic and Fulvic acids. It has been further observed that the relative contribution to the formation of THMs by the humic fraction is greater than that of fulvic fraction, since humic acids react more readily with chlorine (Elshorbagy et al., 2000).

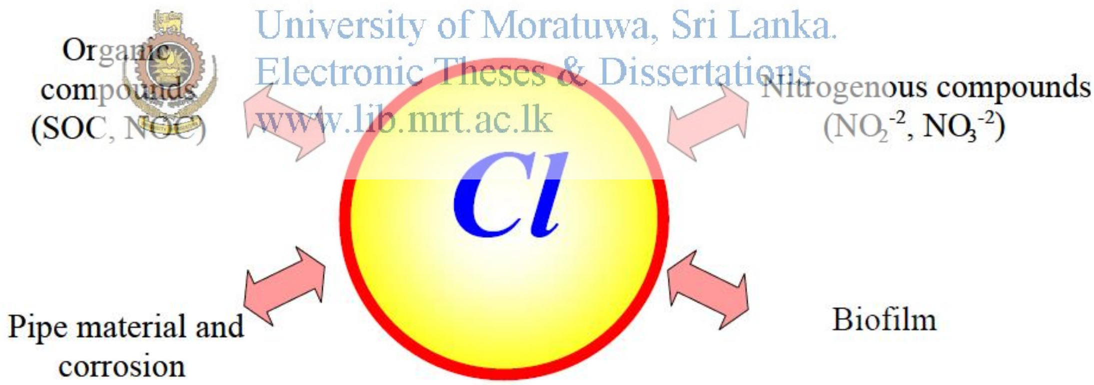


Figure 2.3: Factors effecting on Chlorine decay

It has been identified that the reactivity of the pipe wall will be a function of pipe diameter, hydrodynamic conditions, nature of the pipe material and amount and nature of deposits (Kiene et al., 1998). The following interesting results have been obtained in the same study:

- Chlorine consumption by synthetic materials is negligible and does not appear to be an important parameter for the modelling of Cl decay;
- In contrast, chlorine consumption of old cast iron pipes whose internal surfaces are not protected by a coating can be considered as a major parameter for chlorine

decay modelling. For cast iron or steel pipes, the rate of Cl consumption can be directly considered under the dependence of corrosion phenomena.

- Cl decay due to bulk reactions is very much variable, according to the temperature and organic matter concentration. Variation of kinetics can be predicted by a simple model taking into account the TOC and the temperature.
- Cl decay due to fixed biomass varies according to the colonization time. Influence of biomass should become an important parameter, only for small diameter synthetic pipes fed with water characterized by high biodegradable organic compounds.

2.3.3 Different techniques used in chlorination

Chlorination can be divided into different groups, based on its point of application. These are based on different aspects in water treatment technology.

- Pre-chlorination: The application of chlorine to water, prior to other form of treatment. Usually it is applied just before aeration to assist with the oxidation of inorganic substances or to arrest biological action that may produce undesirable gases in the sludge at the bottom of clarifiers including the prevention of any algae growth at the later stages of the treatment process.
- Post chlorination: The application of chlorine to water, subsequent to any other treatment. This is taken place at the end of the treatment process just prior to the clear water reservoir.
- Re-chlorination: The application of chlorine to water at one or more points in the distribution system, following previous chlorination treatment. This is basically used to optimize chlorination by controlling residual chlorine level above 0.2 mg/L at everywhere, without overdosing at the treatment plant.

The locations of these three different types of chlorination units are presented in the figure 2.4.

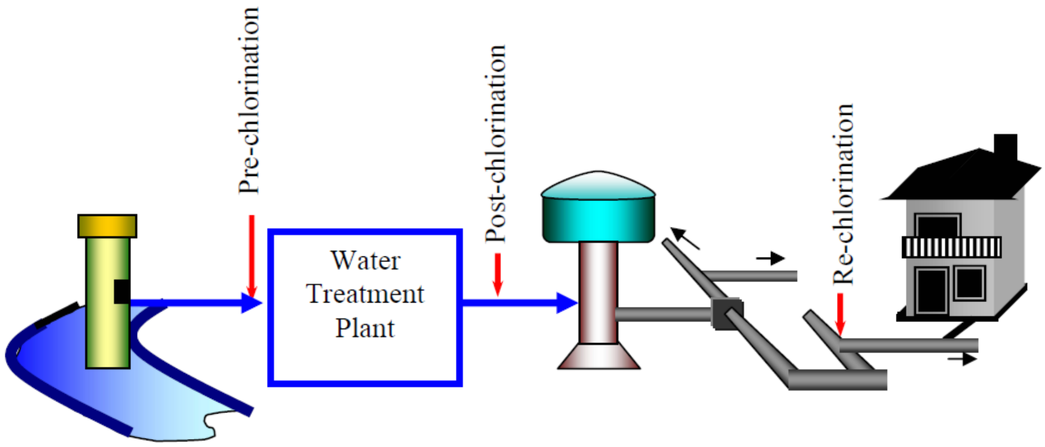


Figure 2.4: Different types of chlorination(Weragoda, 2005)

Since real time measurements of microorganisms surviving disinfection processes are not easy to carry out, the operation of disinfection processes relies on indirect assessment of performance. With chlorine contacting systems, control is most frequently based on the use of residual measurements, on a batch or continuous basis. The feed of chlorine may be controlled automatically to provide a relatively constant residual. The presence of excessive chlorine demand may be symptomatic of a process upset or malfunction.

2.3.4 Formation of disinfection by-products

Disinfection by-products (DBPs) are found in most chlorinated water samples. Typically they are produced in the treatment process as a result of chlorination. The formation of these compounds is a function of precursor concentration, contact time, chlorine dose, and pH (APHA, 1995).

As previously mentioned, Trihalomethane (THM) is the most famous disinfection by products as it is carcinogenic, mutagenic or possibly teratogenic. Aquatic humic and the fulvic acids are the main Trihalomethane precursor, found in surface water bodies. It has been found that the THMs represent between 5% and 20% of the chlorinated products formed during the chlorination process. The main species of THM formation is chloroform ($CHCl_3$), which represents about 82% of the Total THMs formed. (Shafy et al., 2000) Maximum allowable Total THM is given by USEPA as annual average level 80 ppb. The Australian guideline value for THM of 250 ppb is higher than a number of other developed countries including United Kingdom, Japan (100 ppb), USA (80 ppb) France (30 ppb) and Germany (10ppb) (Rizzo et al., 2005).

Aside from THMs, many other compounds, comprising the chlorination by-products, have been found in treated waters.

- Haloacetic acids
- Bromate
- Chlorite
- Haloaldehyde
- Halopicrin
- Cyanogens chloride
- Halophenol
- Chloral hydrate

However most probably, these occur in water in the trace level of ng/L (Lee et al., 2001).

Generation of THM has been shown to be a function of the following factors. (Clark et al., 2001) The effect from each factor may be more or less depending on the existence of them in different water bodies.

- Initial chlorine concentration
- Total organic concentration
- Type of organic precursor
- pH: Increase in pH, increases THM concentration
- Temperature: Increase in temperature, increases THM formation
- Bromide level
- Reaction time
- UV-254 absorbance

Most of the researchers have found that greater the concentration of organic compounds higher the rate of forming THM. Further to that, during chlorination, the bromide is oxidized to bromine, which reacts more readily than chlorine with the organic precursors to form mainly brominated THM (Adin et al., 1990).

For most waters, the reactions of chlorine with natural organic matter (NOM) make up the majority of the chlorine demand. TOC concentration is indicative of the mass of material, whereas spectral absorbance relates more to specific structure and functional groups. Dissolved organic carbon (DOC) is the dissolved fraction of TOC. For NOM, the most commonly used spectral absorbance is the ultraviolet (UV) absorbance (UVA) at a wave length of 254 nm (UVA) which measures conjugated double bonds. The specific UVA (SUVA) is the ratio of UVA to DOC. This value gives an indication of the NOM's nature. SUVA values less than 2 generally indicate a high fraction of hydrophilic non-humic matter with low UV absorbance, a low chlorine demand and low THM formation potential. SUVA values between 2 and 4 are indicative of a mixture of hydrophobic humic and hydrophilic non-humic matter, with medium UV absorbance a higher chlorine demand and higher THM formation potential. SUVA values in excess of 4 are indicative of the presence of humic highly aromatic hydrophobic matter associated with high UV absorbance, high chlorine demand and a high THM formation potential. (Clark et al., 2001).

There are many reasons for THM to become a challenge. Some of these reasons are listed below (Okun, 1996):

- Synthetic organic compounds are very much site specific;
- Lack of knowledge on synthetic organic compounds (only 15 % is known);
- Non-identified organic compounds (only 50% identified);
- Lack of risk assessment models for the very low exposures of contaminants in drinking water;
- Longer time period for syndromes.

These are challenges faced by the present day water engineers too.

Many researches have been carried out on THM formation. In an experiment, done on Bangkhen water treatment plant (Ghazali, 1989), it was identified that, when the chlorine dosage was within the limit of 3 to 5 mg/l, the formation of THM is still below the 100 µm/L, which has been recommended as the maximum permissible limit in the USEPA. However, once the chlorine level increased beyond 7 mg/L, then the level of THM in water had increased to above the permissible limit after contact time of 12 hours. It was concluded that about 50% of total THM forms within the first 3-5 hours. For the balance 50%, it takes longer time of contact. In addition to that, it was found that, THM can be reduced by boiling water. About 50-55% of THM reduction can be observed at the boiling point and further boiling for 10 min reduces about 90% of THM. In another study it has been shown that almost all the THM formation takes place within 24 h (Adin at el, 1999). Therefore, studies have been limited to a time frame of 24 h.

It has been observed that aquatic humic and fulvic acids are the main THM precursors. The plot (Adin at el, 1999) of THM concentration against humic substance levels is a convex shape, suggesting multi-step reduction occurs. In the first step, organochlorine intermediates are produced, and in the second step, these are converted in THM. These kinetics have been modelled to express it mathematically. The figure 2.5 presents the relationship among THM, Cl_2 and Fulvic Acid (FA) concentrations. It is interesting to see here that THM level has gone down while Fulvic acid concentration is being increased, in the absence of Cl.

Another article (Boccelli et al., 2003) on the THM formation explains that there exists a linear relationship between total THM formation and chlorine demand. The linear relationship was estimated using the modelled chlorine demand from a calibrated reactive species model, and using the measured chlorine demand, both of which adequately represented the TTHM formation.

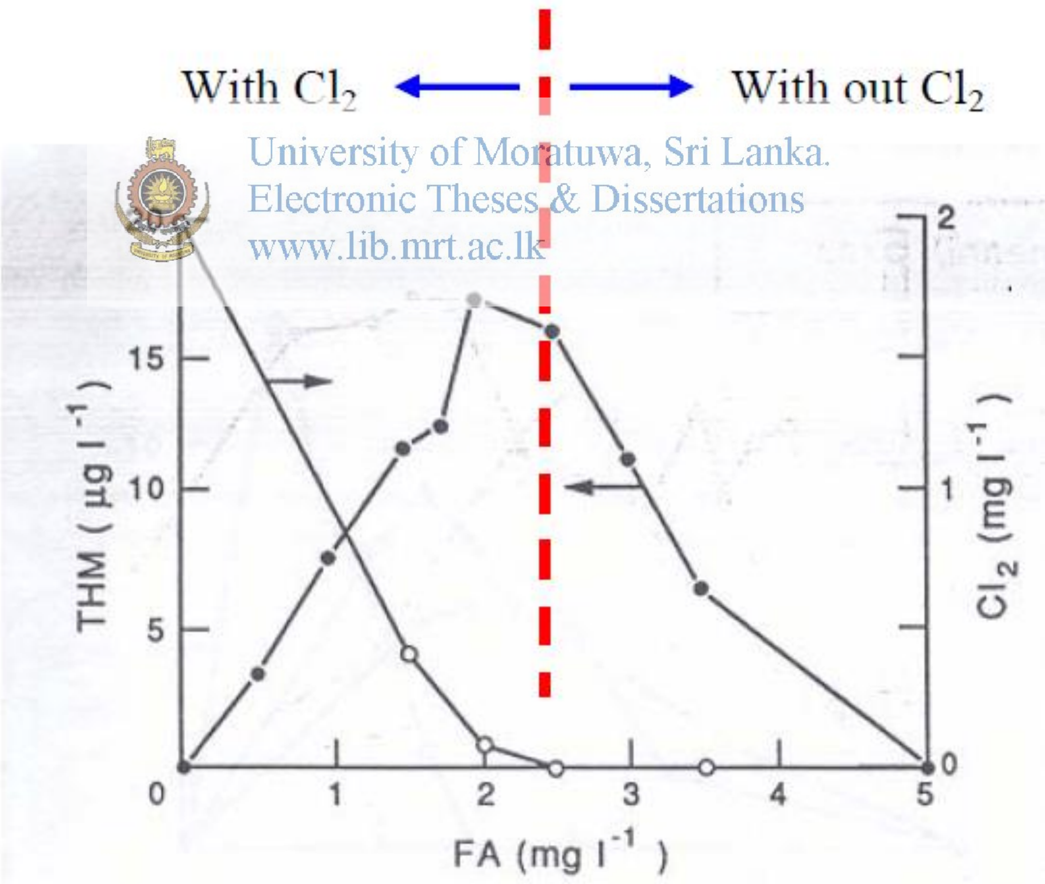


Figure 2.5: Relationship among THM, FA (Fulvic Acid) and Cl_2 concentrations (Adin at el, 1999)

The same variation has been shown against the concentration of Humic acid, too. It is clearly shown in the above graph that the THM variation against Fulvic acid concentration takes two paths at the presence of Cl and at the absence of Cl. The researches have suggested that, there are two competitive pathways for the THM formation:

(1) A direct one;

(2) Via organochlorine intermediates (Adin et al., 1999).

In the past investigations, it has been observed that the occurrence of THMs in chlorinated water may vary significantly according to season and geographical location in the distribution system. These temporal and spatial variations are due to changes in raw and treated water quality as well as in operational parameters related to chlorination. The measurable operation parameters which influence the occurrence of Trihalomethane in the distribution systems are chlorine dose, water temperature, pH and travel time of water within the system. (Rodriguez et al., 2001)

The influence of pre-treatment (UV/visible irradiation, ozone and chlorine dioxide) on chlorine demand and THM formation from NOM was studied by Gallard et al., (2002) and he has found that UV/visible irradiation does not alter THM formation but leads to a higher chlorine demand. Pre-oxidation with ozone leads to a lower THM formation with an unaltered chlorine demand and pre-oxidation with chlorine dioxide reduces THM formation and the chlorine demand.

When the NOM molecules react with oxidants, DBPs are formed. Simultaneously, the absorbance of the NOM changes, resulting an increase in the value of differential absorbance spectrum (Korshin et al., 2001). An interesting correlation has been established in one study on THM formation. It says that the ultraviolet (UV) absorbance in the 250-nm range and TTHMs were closely related and further had found a linear correlation with r=0.9875. Further, the formation of THM was also correlated with the decrease in UV absorbance at 272 nm. But it was strongly dependent on the pH of the water. (Shafy et al., 2000)

UV Absorbance

UV has been widely used to predict natural dissolved organic carbon (DOC) in water or its reactivity in forming disinfection by-products during chlorination process. Because of easy measurement, UV_{254} offers potentially simple and reliable methods to quantify the contribution of organic carbon in water to formation of DBPs during chlorination. The TOC and UV_{254} can provide insight into the nature of the organics present and the potential for DBP formation.

2.3.5 Importance of chlorination against other disinfection methods

Chlorine remains still as the overwhelming choice for drinking water and wastewater disinfection. It has many advantages such as:

- Effectiveness against many organisms;
- Readily availability;
- Relatively low in cost;
- Simple in operation;
- Higher reliability;
- Residual effects.

2.3.6 Factors affecting the rate of chlorine decay

There are three main factors that frequently influence chlorine consumption. They are namely:

- Reactions with organic and inorganic chemicals in reduced form (eg. Ammonia, Sulfides, Ferrous ion, Manganous ion, Humic material) in aqueous phase;
- Reactions with biofilm at the pipe wall;
- Consumption by the corrosion process; Free Chlorine is consumed on the one hand by water (oxidation of dissolved organic compounds) and on the other hand by the internal wall of pipes. Indeed, it can react firstly with the fixed biomass and secondly, with the materials themselves.

In addition to these, some researchers stated that residual free chlorine of 0.2 mg/L is sufficient to guarantee and control the re-growth of bacteria in a distribution system. But in one study, it is reported that biofilm was formed in distribution networks with the free chlorine residual less than 0.5 mg/L. (Shafy et al., 2000) Therefore, this has to be further studied to confirm.

2.4 Evolution of Water Safety Plan Approach

There is extensive evidence that inadequate management of drinking-water distribution systems has led to outbreaks of illness in both developed and developing countries. The causes of these outbreaks and the range of chemical and microbial hazards involved are diverse. Between 1981 and 2010 in the United States of America (USA), 57 outbreaks were associated with distribution system faults, leading to 9000 cases of illness (CDC, 1981, 1982, 1983, 1984; St Louis, 1988; Levine, Stephenson & Craun, 1990; Herwaldt et al., 1991; Moore et al., 1993; Kramer et al., 1996; Levy et al., 1998; Barwick et al., 2000; Lee et al., 2002; Blackburn et al., 2004; Liang et al., 2006; Yoder et al., 2008; Brunkard et al., 2011; Hilborn et al., 2013). The most common faults were cross-connections and back-siphonage; other faults included burst or leaking water mains, contamination during storage, poor practices during water main repair and installation of new water mains, pressure fluctuations and leaching from pipework; a significant proportion of faults are unknown. Elsewhere, outbreaks of illness have been associated with low water pressure and intermittent supply. (Hunter et al., 2005)

The health outcomes from distribution system–related outbreaks can be severe, but risks are preventable, providing sufficient attention is paid to preventing contamination. Effective implementation of the World Health Organization's (WHO) Guidelines for Drinking-water Quality (WHO, 2011) requires application of an integrated risk management framework based on a multiple-barrier approach that extends from catchment to consumer. This includes protection of water sources, proper selection and operation of treatment processes and management of distribution systems. In recent years, much attention has been paid to preventing contamination of water sources as a first step, followed by selecting and reliably operating treatment processes. Evidence from the USA shows that this has been successful in reducing waterborne outbreaks associated with inadequate treatment, particularly of surface water supplies (Craun et al., 2006; Craun, 2012). Despite this progress, the regular occurrence of outbreaks associated with distribution systems suggests that too little attention is being paid to sound management of these systems (Craun & Calderon, 2001; Craun et al., 2006). Contamination of distribution systems occurs after treatment, meaning that, with the exception of residual disinfectants, which provide some protection against bacterial and viral hazards, there are no further control measures for contaminants that gain entry to distribution systems or are released from pipe materials. Hazards introduced through faults in distribution systems typically flow directly to consumers. Integrity of distribution systems represents the final barrier before delivery of drinking-water to consumers, and management of risks in these systems should be incorporated in well-designed water safety plans (WSPs).

The issue of maintaining water safety in distribution systems was identified as a significant concern at a meeting of experts convened by WHO in July 2011 in Singapore. This was based on existing evidence that inadequate design, construction and management contribute to a significant proportion of drinking water–borne disease. In addition, stresses caused by rapid urbanization, population growth and ageing infrastructure could further exacerbate problems with distribution systems. It was agreed that additional guidance on the application of good management practices for distribution systems was required.

2.5 Studies on relationships between THM formation and other parameters in the distribution system

The generation of TTHMs has been shown to be a function of various water quality parameters and chlorine conditions, including total organic carbon, the type of organic precursor, chlorination level, pH, temperature, bromide level, reaction time, and UV absorbance (Clark, 1998).

In 1974, chloroform, a product of the reaction of chlorine and naturally occurring organic matter, was identified in disinfected drinking water. Since that time a number of other DBPs have been identified, including THMs, by-products other than chloroform (e.g., bromodichlorometane), haloacetic acids (HAAs), haloacetonitriles, haloketones, and haloaldehydes. All of the disinfections mentioned are reactive; ozone, chloramines, and chlorine dioxide results in both organic and inorganic by-products. More than 500 DBPs have been identified in tap water (Clark, 1998).

2.5.1 Clark, 1998

Several models have been developed to explain the formation of TTHM in chlorinated water. A simple model (Clark, 1998), presented below, describes TTHM formation kinetics.

The general chemical reaction between two chemicals is as follows

$$aA + bB \longrightarrow pP$$

Based on that an equation, the kinetics of THM formation can be developed.

$$\frac{dC_p}{dC_A} = -T \text{ , } [T = (k_P/k_A)]$$

Where;

k_p - Reaction rate for the formation of products (1/h),

k_A - Reaction rate for the formation of substance A (1/h),

C_A - concentration of substance A (mg/L),

C_p - Concentration of product P (mg/L).

If we let, $C_p = C_A y$

Then,

$$C_A \frac{dy}{dC_A} + y = -T$$

Assuming, $C_A = C_{A0}$, at y=0

Then, $C_P = T\ (C_{AO} - C_A)$

Suppose, $C_p = TTHM$

$$TTHM = T\left\{C_{AO} - \left[\frac{C_{AO}(1-R)}{1-\mathrm{Re}^{-ut}}\right]\right\} + M$$

$$R = (aC_{B0}/bC_{A0}) \text{ and } u = \left(\frac{bC_{Ao}}{a} - C_{Bo}\right) * k_A,$$

Where,

T - Dimensionless parameter,

C_{AO} - Initial chlorine residual of A (mg/L),

C_{BO} - Initial chlorine residual of B (mg/L),

a - Coefficient of reacting substance A,

b - Coefficient of reacting substance B,

M - Estimated value of TTHM at time zero (mg/L).

k_A - Reaction rate constant for formation of A

A linear correlation between the cumulative chlorine decay and the cumulative THMs formed in the pipelines with $R^2 = 0.913$ has been observed by Shafy et al. (2000). Another experiment has been concluded with a linear relation between the cumulative DBPs and $-\Delta A_{272}$ (Korshin et al., 2002). These studies will support in exploring the nature of NOM-chlorine interactions as well monitoring of DBPs in water distribution systems. In addition to that, the relationship between THM formation potential and the UV absorbance at 254 nm also studied. This study has been concluded with a well defined correlation between those two parameters (Gallard et al., 2002).

2.5.2 Xin Li et al., 2005

The rate of Trihalomethanes (THM) formation was experimentally observed to be first-order with respect to chlorine,and first-order with respect to humic acid precursors, and the overall reaction order was second-order. THM formation rate expression was formulated as a function of the concentration of THM Formation Potential (THMFP), residual chlorine concentration, reaction time and reaction temperature. A model is developed to estimate THM in water distribution systems. Since the calculated results are close to the measured values in the distribution system, it is suggested that this model is applicable to actual water distribution systems.

$$\frac{d[THM]}{dt} = k_0[Cl_2]^n[TOC]^m$$

where: [THM] is concentration of THM; [Cl2] is concentration of free chlorine residual; [TOC] is concentration of precursors; n, m are orders of reaction; k_0 is rate constant.

Both m and n are experimentally found to be 1.0, the rate of THM formation is first-order with respect to chlorine, and first-order with respect to precursors, and the overall reaction of THM formation is the second order reaction.The formation of THM can be written as:

$$\frac{d[THM]}{dt} = k_0[Cl_2][TOC]$$

The potential of natural organic material in raw water react with chlorine to form THM, is called THM formation potential (THMFP). THMFP and THM were adopt to substitute TOC, then the THM reaction rate is described as:

$$\frac{d[\mathrm{THM}]}{dt} = K[\mathrm{Cl_2}][\mathrm{THMFP} - \mathrm{THM}]$$

Integrating the equation with $[Cl_2]$ kept constant during the reaction and [THM] equals zero, when t = 0, yield

$$\ln \frac{[\mathrm{THMFP}]}{[\mathrm{THMFP} - \mathrm{THM}]} = Kt[\mathrm{Cl_2}] \qquad \text{Eq.04}$$

where: $[Cl_2]$ is concentration of free chlorine residual (mg/l); [THMFP] is concentration of THMFP (µg/l); [THM] is concentration of THM (µg/l); K is rate constant ($\mathrm{lmg^{-1}h^{-1}}$); t is reaction time (h).

The concentration of THM was given by:

$$[\mathrm{THM}] = [\mathrm{THMFP}] - [\mathrm{THMFP}]e^{-Kt[\mathrm{Cl_2}]}$$

The K was estimated by substituting the experimental results of [THM] and $[Cl_2]$ into Eq. 04 using the linear least squares method. The characteristics of water samples are: T = 25.1^0C, pH = 7.90, TOC = 3.12 (mg/l), $[Cl_2]_0$ = 1.50 (mg/l), [THMFP] = 40.07 (µg/l). Considering THM formation and chlorine decay during 50 h, the value of K was obtained as: 0.117($\mathrm{lmg^{-1}h^{-1}}$).

In water distribution system, when t = 0, [THM] =$[THM]_0$,

$$[\mathrm{THM}] = [\mathrm{THMFP}] - [\mathrm{THMFP} - \mathrm{THM_0}] \times \exp\{-Kt[\mathrm{Cl_2}]\}$$

2.5.3 Damien Mouly et al., 2005

This study describes the behavior of Trihalomethane in three French water distribution systems and develop a mathematical model to predict concentrations in the water distribution system using data collected from treated water at the plant (i.e. the entrance of the distribution system). The average Trihalomethane concentration in the three water distribution systems ranged from 21.6 mg/L to 59.9 mg/L. The increase in THMs between the treated water at the plant and a given point in the water distribution system varied by a factor of 1.1 to 5.7. A log-log linear regression model was constructed to predict THM concentrations in the water distribution system. The five variables used were THM concentration and free residual chlorine for treated water at the plant, two variables that characterize the reactivity of organic matter (specific UV absorbance (SUVA). an indicator developed for the free chlorine consumption in the treatment plant before distribution δ) and water residence time in the distribution system.

The modelling approach chosen in this study aimed at predicting THM concentrations at the point of consumption. The ultimate, long-term goal was to provide a tool for estimating THM exposure rates in the French population using data available from the SISE-eaux national database.

The model chosen was a log-log linear regression model

$$\mathrm{Log}(Y) = \mathrm{Log}(b_0) + \sum_{i=1}^{p} b_i\, \mathrm{Log}(X_i)$$

Y is the THM concentration in the water distribution system and X_i, i =1 to p are the explanatory variables. Other than the residence time, all of the covariables were derived using measurements taken of the treated water at the plant.

Based on published studies, two composite explanatory variables were created [for the model used here]:

(i) SUVA calculated at the treated water at the plant:

$$\mathrm{SUVA\_tp} = \frac{\mathrm{UVAbs254\ nm}}{\mathrm{TOC}}$$

[SUVA_tp] is expressed in L mg^{-1}m^{-1}; [UVAbs254 nm] is a measure of UV absorbance at 254 nm (m^{-1}); [TOC] is a measure of total organic carbon (mg L^{-1})

(ii) a variable, arbitrarily noted as 'δ', that gives the chlorine consumption rate at the plant and corresponds to the following equation:

$$\delta = \frac{(\mathrm{Cl_2\ _{inj}} - \mathrm{Cl_2\_tp})}{\mathrm{CT}} \times \theta$$

where ‘δ’ is expressed in mg $^{0}CL^{-1}$ min^{-1}, $Cl_{2\ inj}$ is the dosage of chlorine relative to water flow as injected at the treatment plant, expressed in mg L^{-1}; Cl_{2_tp} is the concentration of free residual chlorine in treated water at the plant, expressed in mgL^{-1}; CT is the chlorine contact time between the chlorination point and the treated water at the plant, expressed in minutes; Θ is the water temperature of the treated water at the plant expressed in ^{0}C.

2.5.4 Manuel J.Rodriguez et al., 2001

THM concentrations vary significantly (from 1.5 to 2 times, depending on the utility) between finished waters as they leave the plant and water at the system extremities. When water temperature exceeds $15^{0}C$, spatial THM variations are particularly high (from 2 to 4 times, depending on the utility). The development of multivariate regression models showed that water temperature was a better predictor of THM seasonal variability than chlorine dose, surrogates of natural organic matter and pH. To better identify the effects of those other parameters on THM formation, it would have been necessary to study THM variations during relatively short periods within which variations of temperature were few and changes in water quality were appreciable. Also, initial THM formation (in finished waters leaving the plant) was a good predictor of THM levels at distribution system extremities.

Results concerning variability of THMs and the number of factors influencing their formation and fate confirm that it is difficult for water utility managers to satisfy the dual objectives of the chlorination process: maintaining an acceptable microbiological water quality while minimizing THM formation.

2.5.5 Shafy et al., 2000

The low velocity and the large volume of reservoirs increase the residence time and correspondingly provide conditions for more chlorine decay and accordingly an increase in THM formation. There was a linear correlation between the cumulative chlorine decay and the cumulative THMs formed in the pipelines with R^2= 0.913.

This relationship can be described as the following:

$$THM = A + B * \Sigma DCl$$

where THM is the trihalomethane concentration at any place in pipelines [μgl^{-1}] and ∑DCl is the cumulative decay of chlorine residual from the beginning of the pipeline to this place [mg l^{-1}], A and B are constant coefficients to be calibrated according to THMs formed in the WTP and other water characteristics.

The correlation between THM formation and residence time was exponential with R^2= 0.91. A very good correlation was found between the residence time and THM and $CHCl_3$ formation. The increase of THM and $CHCl_3$ concentrations can be formulated as Exponential functions of the residence time t (or first order increase) as the following:

$$THM_t = THM_o \exp(kt)$$

$$CHCl_{3_t} = CHCl_{3_0} \exp(kt)$$

where k is the coefficient of first order increase, THM_t and $CHCl_{3t}$ are the concentrations of Trihalomethane and chloroform (respectively) at any time, and THM_o and $CHCl_{30}$ refer to the concentrations of them at the initial time. These formulae can be used to predict the concentration of THM and $CHCl_3$ in the transporting pipelines after the determination of the coefficient k.

2.5.6 Jianrong Wei et al., 2010

A low but definite with a small relationship (r =0.287) was obtained between HAA formation and TOC, and a moderate correlation with a substantial relationship (r =0.415) was obtained between HAN formation and TOC. However, there was no apparent correlation between TOC and THMs. In general, greater DBP levels are formed in waters with higher concentrations of TOC (USEPA, 2006). TOC removal may be a possible reason that is used to explain the lack of an apparent correlation between TOC and DBPs. There were likely a lot of variations in the TOC removal between the various plants of Beijing City, which obviously impacted by-product formation. Another reason was that TOC is an indicator of mass organic substance and does not differentiate between the various chemical compounds that make up the precursor compounds (USEPA, 2001).

Water temperature was strongly correlated with chloral hydrate (CH), chloropicrin (CP) and THMs. But there was no apparent correlation between water temperature and other DBPs. The rates of formation of most DBPs increase with increasing temperature.

However, high temperature conditions in the distribution system promote the accelerated depletion of residual chlorine, which can mitigate DBP formation and promote biodegradation of DBPs (especially HAAs) unless chlorine dosages are increased to maintain high residuals (Singer and Reckhow, 1999). All of these reasons affect the relationship between water temperature and DBPs. A strong positive correlation existed between applied chlorine dose and most groups of DBPs except CH. As the concentration of chlorine or chloramines increases, the production of DBPs increases. Formation reactions continue as long as precursors and disinfectant are present (Krasner, 1999). Chlorine dosage which had no apparent correlation with CH may be may be due to the quality of water source, water temperature and also the material properties of the water pipes. No significant correlations were observed between DBP levels and pH. In general, THM formation increases with increasing pH, whereas the formation of HAAs and other DBPs increases with decreasing pH (USEPA, 2006). However, in Beijing City, the pH of water sample ranged from 6.82 to 8.55. And the pH only changed slightly. The pH value could hardly affect the formation of DBPs.

2.5.7 Bixiong Ye et al., 2009

TOC and UV254 have definite correlations with total THM, but have non-significant relationships with total HAA. In the studied pH range of 6.5–8.5 for drinking water, the total THM concentration increased with the increasing of pH value, but the total HAA concentration slightly decreased. A low but significant relationship ($r = 0.26$, $p < 0.01$) occurred between total THM and applied chlorine dosage. Similar relationship ($r = 0.21$, $p < 0.01$) was found between total HAA and applied chlorine dosage. When the water temperature was low, the variation of THMs and HAAs was little, but in warmer water, the concentration of THMs and HAAs varied quickly. The extent of bromine incorporation into the DBPs increases with increasing bromide ion concentration. Based on the effect of chemical elements for the DBPs remove effect, the polyferric chloride could be a preferred flocculant agent in waterworks.

2.5.8 Richard J. Summerhayes et al., 2011

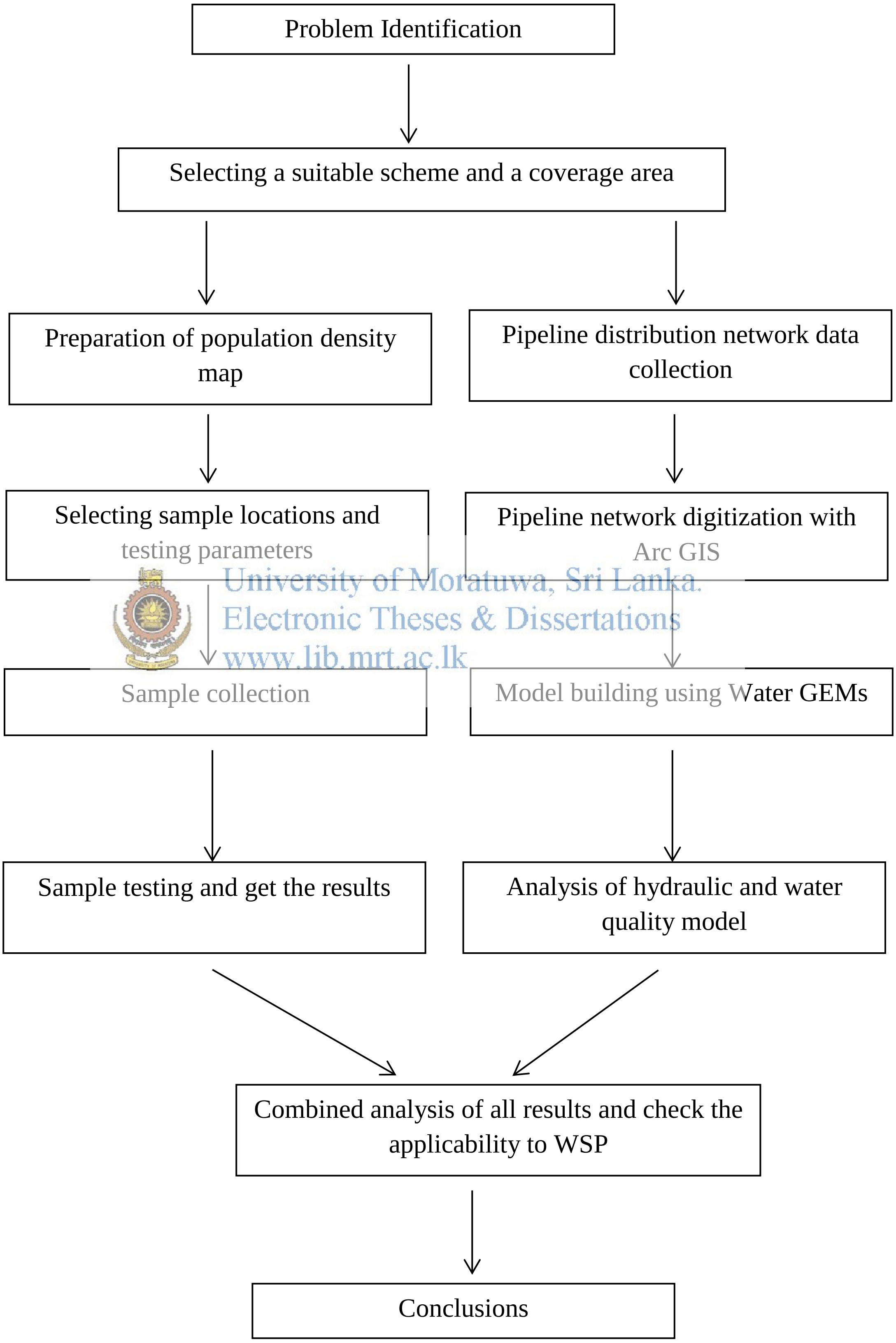
Chloroform was the predominate THM in two-thirds of the rural water utilities. Higher concentrations of THMs were found in chlorinated water distribution systems compared to chloraminated systems, and in distribution systems sourced from surface water compared to ground water or mixed surface and ground water. Ground water sourced supplies had a greater proportion of brominated THMs than surface water sourced supplies. There was substantial variation in concentration of THMs between seasons and between periods of drought or no drought. There was a moderate correlation between heavy rainfall and elevated concentrations of THMs.

2.5.9 Rafael J.Garcia et al., 1996

Data obtained were correlated statistically with the chlorination dosages in the treatment plants and the distribution system, the distances run by the water, residual free chlorine and total chlorine, the total organic carbon (TOC), pH and temperature. The prechlorination dosage did not correlate strongly (P = 0.1268) with chloroform content at the first point of the distribution system, while that of postchlorination and rechlorination did not correlate at all. The organic matter, measured as the TOC, showed a positive correlation (P = 0.0322), with a consumption of free chlorine (R =--0.327, P = 0.0190) and total chlorine (R =-0.290, P = 0.0393) that was proportional to the content in THMs. However, the distance among the six points of the distribution system-an approximate means of estimating the reaction time-yielded conflicting results. Temperature and pH proved to be the parameters with the strongest influence. Temperature alone did not show linear dependence, while pH did (R = 0.665, P = 0.0001), showing a dramatic increase in THM levels on two sampling dates with exceptionally high pH levels. Functions of these two parameters permitted the elaboration of a predictive mathematical model (R = 0.995, P < 0.0001) in which increasing values of pH and temperature are seen to increase the level of chloroform up to a given temperature value (To = 17.30^{0}C) after which a sharp decrease in the chloroform content occurs. This value was comparable with that obtained with a similar model in the finished water treatment plants. A global modeling of both systems (treatment plants and distribution system) was also possible (R = 0.827, P = 0.0001), with a Tc value of 18.74°C for each pH.

3. RESEARCH METHODOLOGY

3.1 Flow diagram of Methodology



3.2 Selecting a suitable scheme for the analysis

After carrying out a feasibility study on each scheme individually, one particular scheme was selected out of 15 sub-schemes in Kandy South Region for the final analysis in detail. Following factors were considered when selecting Maligathenna pipeline distribution network for a pilot study.

- Pipeline Distribution length was around 60km, which is longer than the other schemes and well above the average length of schemes. Therefore it covers a larger area, so that the sampling points could be scattered well.
- Located around 10-20km away from treatment plant, where the age of water is considerably high compared to other schemes.
- More pipeline attribute data is available than other schemes.

Thus, the objective of selecting this particular scheme was to study the worst case scenario within this particular system. Therefore, if the risks of contaminations in this scheme is not significant, we could assume that the risk is not significant in other schemes in this region as well.

3.3 Selection of sampling points

Larger distribution networks generally require more samples to characterize water quality due to greater differences in network attributes such as flow rates, water retention times, pipe material and pipe age. Larger networks may also receive water from different service reservoirs, and there may be distinct geographical discontinuities, such as two suburbs or towns separated by a major road or river. A common approach is to split larger networks into zones or sub-districts with the view to conducting a verification monitoring regime within each zone that effectively characterizes water quality in that zone.

Accordingly there are 15 sub-schemes coming under Kandy South region water distribution network where all the schemes are fed by Meewathura Treatment Plant. However the scope of this study has been limited to Maligathenna scheme. Total distribution network length is around 60km. Diameters vary from 63mm to 280mm.

The common practice among water utilities is to rotate among designated sampling sites across the distribution system. Here, the aim is to characterize water quality within the zone effectively and enable comparisons of water quality over time for particular sections of the system. Rotation of sampling sites avoids the problem of sampling from the same site each time, which could give a misleading characterization of water quality. It is important that the sampling frequencies and locations are selected to provide the greatest confidence that all parts of the system are operating within the target ranges and, in the case of certain microbial parameters, free from contamination.

The location of sample points across each zone should reflect the number of people served. Different parts of the zones may include branch pipelines or loops, different pressure zones or areas receiving water from different sources or different treatment plants. Apart from the Maligathenna scheme, water samples were collected from the distribution system in Mahakanda, Sarasavigama, University, Hindagala, Pilimathalawa, Danture, Menikdiwela, Kadugannawa, Handessa and Peradeniya areas. A total of 50 points were tested from August, September and October. Treatment plant, service reservoirs and user end points were selected for the purposes of water quality parameters and DBP measurements. The selection of end user sampling points was selected based on population served and it was (1 sample/5000 persons). The four THM species studied were Trichloromethane(TCM), bromodichloromethane (BDCM), dibromochloromethane (DBCM), Tribromomethane (TBM). Other DBPs that could be present but not analyzed were 1,1,1-Trichloroethane (TrCEa), Carbon tetrachloride (CTC) ,Trichloroethylene (TrCEe), Tetrachloroethylene (TeCEe) ,1.2-Dibromoethane (DBEa) ,1.2-Dibromo-3-chloro-propane (DBCPr).

3.4 Distribution network data collection and interpretation

Kandy South (Meewathura) Treatment Plant is having the treatment capacity of approximately 30,000m^3/day. All 15 sub-schemes are managed by respective OIC. The main assets of the system were pipelines, valves, flow meters, break pressure tanks, endcaps etc. OICs are having pipe distribution maps of their regions, but most of them are not updated for a long time. I discussed with them, collected the information they have and referred old design drawings prepared during the construction stage of the schemes to collect more informations.

Then I digitized all the water distribution pipelines of 15 water supply schemes using ARC GIS 10.1 software with the help of Google Earth software package. Collected attributes were then assigned to the pipelines. There were 375km long pipeline distribution network in the Kandy South region and 60km long pipe distribution lines in Maligathenna scheme.

ARC GIS

ArcGIS is a geographic information system (GIS) for working with maps and geographic information. It is used for: creating and using maps; compiling geographic data; analyzing mapped information; sharing and discovering geographic information; using maps and geographic information in a range of applications; and managing geographic information in a database.

3.5 Pipeline distribution network modelling

3.5.1 Developing Hydraulic Model, calibration and analysis

Hydraulic model and the associated water quality model of Maligathenna scheme were developed using Water GEMs V8i software package. Elevations of nodes were determined by a digital elevation model (DEM). Flow data, reservoir data and pumping data were collected from SCADA (supervisory control and data acquisition) system were used to monitor the pumping rates and reservoir level variations. The hydraulic model was run for both the present demand and future demand. Present average demand is estimated as the 136.83m^3/hour and future average demand is estimated as 156m^3/hour. Hourly demand changes were obtained from the peak factors as shown in the figure 3.1

Model calibration was carried out for pressure using the field pressure data which were measured using a portable pressure gauge. Field pressure values were taken at specified sampling locations and compared with the model values.set of data given in table 3.1. The model is acceptable if the maximum difference between model values and field values is 0.2 bars for all readings(Water Authorities Association and WRc, 1989). Referring to the table 3.1 hydraulic model is considered as acceptable though 4 points are outliers (Refer Appendix B).

Table 3.1: Hydraulic model calibration data

Address	Model pressure value bar	Field pressure value bar	Difference bar
Malwatta Estate,Arambegama,Pilimatalawa	8.80	8.5	0.30
192,Kudaoya,Pilimatalawa	8.40	8.2	0.20
Giragama Estate,Pilimatalawa	7.16	7.2	0.04
91/1,Urapola,Kudaoya,Pilimatalawa	7.61	7.75	0.14
Kuruduwatta,Pilimatalawa	6.70	7.0	0.30
Kotabogoda,Kuruduwatta,Pilimatalawa	4.80	4.6	0.20
Kotabogoda ,Kadugannawa	7.43	7.8	0.37
5b3,Siyabalagoda,Danture	7.80	7.6	0.20
Sinhagiri hotel,Danture	7.80	8.2	0.40
Walgampaya,Danture	1.19	1.2	0.01

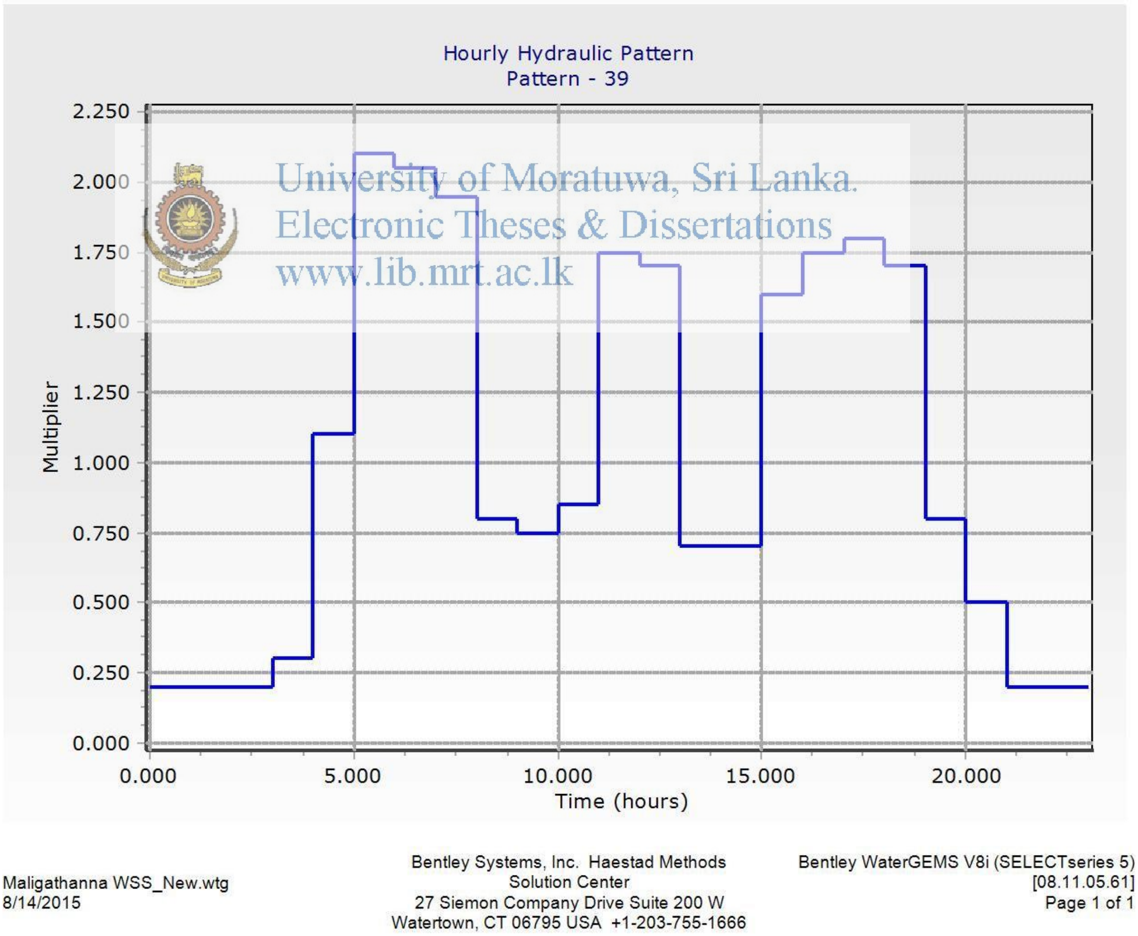


Figure 3.1: Peak factors used to calculate hourly demand of the system

3.5.2 Water Quality Model Analysis

Water age, defined as the time taken for the water to travel from source to consumer, is a factor influencing water quality deterioration within the distribution system. It is a hydraulic parameter and depends primarily on water demand, system operation and system design. In addition water age is significantly affected by storages, excessive capacities in the distribution system to meet emergency requirement and low demands during initial period of design (Rossman, 2000). Hydraulic analysis for an extended period was performed using models of Water GEMs to obtain water age.

The water quality model was run mainly to analyse the water age and residual concentration within the pipe distribution system. Age analysis was performed for water in the system, assuming an initial age of 0 for all nodes. The water from the reservoir will be an infinite supply of new water, so the age of water elsewhere in the system will be a reflection of time from the start of the run and how long ago the water left the reservoir. The analysis will be run for a 2-week period (336 hours), in order to determine the equilibrium point of the system. Water age vs time graph was observed to monitor the time taken to stabilize the system age. Once a repeating pattern is reached, the age of the water fluctuates between two fix values within a 24-hour period. After that the water age of the sytem was supposed to be in equilibrium, hence the age value could be estimated at any time period. The samples were collected in the morning from 9 am to 12.30 pm. Therefore the average age within that period was taken for the analysis.

Constituent analysis was carried out to monitor the chlorine residuals in the system over time under present demand as well as future demand. Following parameter values were used for the analysis.

- Bulk Reaction Rate -0.10 (mg/L)^(1-n)/day
- First Order Wall Reaction Rate -0.08 m/day
- Diffusivity 1.2e-9m^2/s
- Initial chlorine concentration 0.2mg/l

Water quality model was calibrated with the actual RCl values measured at site. (Refer table 4.3). The process is discussed under section 4.2.1.

Water GEMs V8i

WaterGEMS® is a multi-platform hydraulic and water quality modeling solution for water distribution systems with advanced interoperability, geospatial model-building, optimization, and asset management tools. From fire flow and constituent concentration analysis, to energy consumption and capital cost management, WaterGEMS provides an easy-to-use environment for engineers to analyze, design, and optimize water distribution systems.Further WaterGEMs users enjoy the power and versatility afforded by working across CAD, GIS, and stand-alone platforms while accessing a single, shared, project data source. (http://www.wateronline.com)

3.6 Sample Collection and Analysis for RCL, THM, TOC, Turbidity and Conductivity

Sample collection work was carried out at predefined locations marked in the location map. Excact locations of the distribution network was found by using the GPS. In addition samples were collected from all the reservoirs in Kandy South Region. RCl values were determined insitu using the DPD colour comparator method with Hach test kit with DPD1 powdered tablet.

Samples for THM were collected to amber coloured plastic bottles. Prior to sample collection $Na_2S_2O_3$ (s) was added to the bottles as chlorine neutralizing agent. Collected samples were stored at 25 ^{0}C and analyzed within two weeks. Kuivinen and Johnsson, 1998 headspace method was used to determine the THMs and TrCEa, CTC, TrCEe, TeCEe, DBEa, DBCPr. Analyses of these DBPs were performed by gas chromatography using a Thermo scientific trace 1300 GC equipped with an electron capture detector equipped with headspace auto sample and heating agitator.

In order to monitor the precision and reliability of analytical results, no less than 50% replicate samples were examined in DBP analysis. Field blanks, which are accompanied with samples to the sampling sites were used to determine any background contamination. Method blanks and spiked blanks (standards spiked into solvent) were analyzed and were subtracted from the analytical results to remove the contribution of contamination in laboratory. (Refer Appendix A)

TOC is the amount of carbon bound in an organic compound and is often used as a non-specific indicator of water quality. TOC level of the water is determined by the TOC analyser. Greater Kandy Laboratory of NWSDB was not having a TOC analyser to determine the TOC level. Therefore I got the assitance of Environmental Engineering Laboratory of University of Peradeniya to test the samples for TOC. Since there could be a certain relationship between the THM level and TOC level of water, TOC values also were determined. Those values were also plotted in a map and analysed for a probable correlation. Turbidity was measured using the laboratory turbidity meter following the standard methodology to determine turbidity. Conductivity was also measured by conductivity meter used in the Greater Kandy Laboratory.

In order to assess the impact of retention time of each reservoir in the region a new parameter was introduced assuming that a higher retension time could be expected when the number of connections served are less or the capacity of the reservoir is high. That is the proportion between the capacity of the reservoir and the number of connections being served by that particular reservoir. If this new parameter value is high, the water retention time is supposed to be longer.

After compiling all the field, laboratory and model data, those were critically analyzed to identify the probable coorelations among them and to identify the variation patterns throughout the Maligathenna distribution system. Probable outliers of each data sets were identified and omitted before analysis. Microsoft Excel was used to plot the data against each other and used Linear and Polynomial trendlines to estimate the R^2 value. The spatial variation of each parameter was plotted using ARC GIS software.

3.7 Applying Water Safety Plan concepts

According to the WSP possible hazards to any water distribution system are in three types.

- Microbial
- Chemical
- Physical

In addition possible hazardous events which could affect the integrity and quality of the distribution system are also in three categories.

- Physical integrity
- Hydraulic integrity
- Water quality integrity

After analysing all the results, the threats to the water quality of the distribution system in the above all forms could be identified. The severity could be assessed by comparing those parameter values with the accepted standards in practice. Some of the hazards may not have come across earlier by the NWSDB and some hazards are known but the severity is not assessed. Hence the appropriate control measures could be introduced to mitigate those negative effects to the distribution system. Those control measures could be implemented either during the system design stage or operation and maintenance stage.

4. ANALYSIS, RESULTS AND DISCUSSION

4.1 Introduction

The Chapter four consists of the analysis, results and discussion of collected data in order to achieve the research objectives which have been mentioned in Chapter One. Data collected from field survey and laboratory investigations, hydraulic and water quality modelling and geographically analyzed data using ARC GIS software were used in the analysis.

4.2 System Assessment

Kandy South (Meewathura) Treatment Plant is having the treatment capacity of approximately 30,000m^3/day. All 15 sub-schemes are managed by respective OIC. Total distribution network length of Maligathenna Scheme is around 60km. Diameters vary from 63mm to 280mm PVC pipes. Distribution network is fed by a 356m^3 capacity reinforced concrete reservoir located at the highest location of the area (594MSL). The scheme is serving around 3702 connections at present. The main assets of the system were pipelines, valves, flow meters, break pressure tanks, endcaps etc.(Figure 4.1) The probable risks identified are as follows.

- Formation of harmful DBPs (Mainly THM)
- Insufficient RCl level leading to microbiological contamination
- Water stagnation
- Unlikely water pressure conditions
- Unlikely TOC, Turbidity, Conductivity levels

Population Density maps

With the help of population density map, it is easy to understand the overall scattering of population density in the region. Densely populated areas and less populated areas of the region were identified and customized the sampling work accordingly (Figure 4.2). In addition it was attempted to correlate the population density with the water quality and hydraulic parameters. However due to inadequate data a good corelation was not identified.

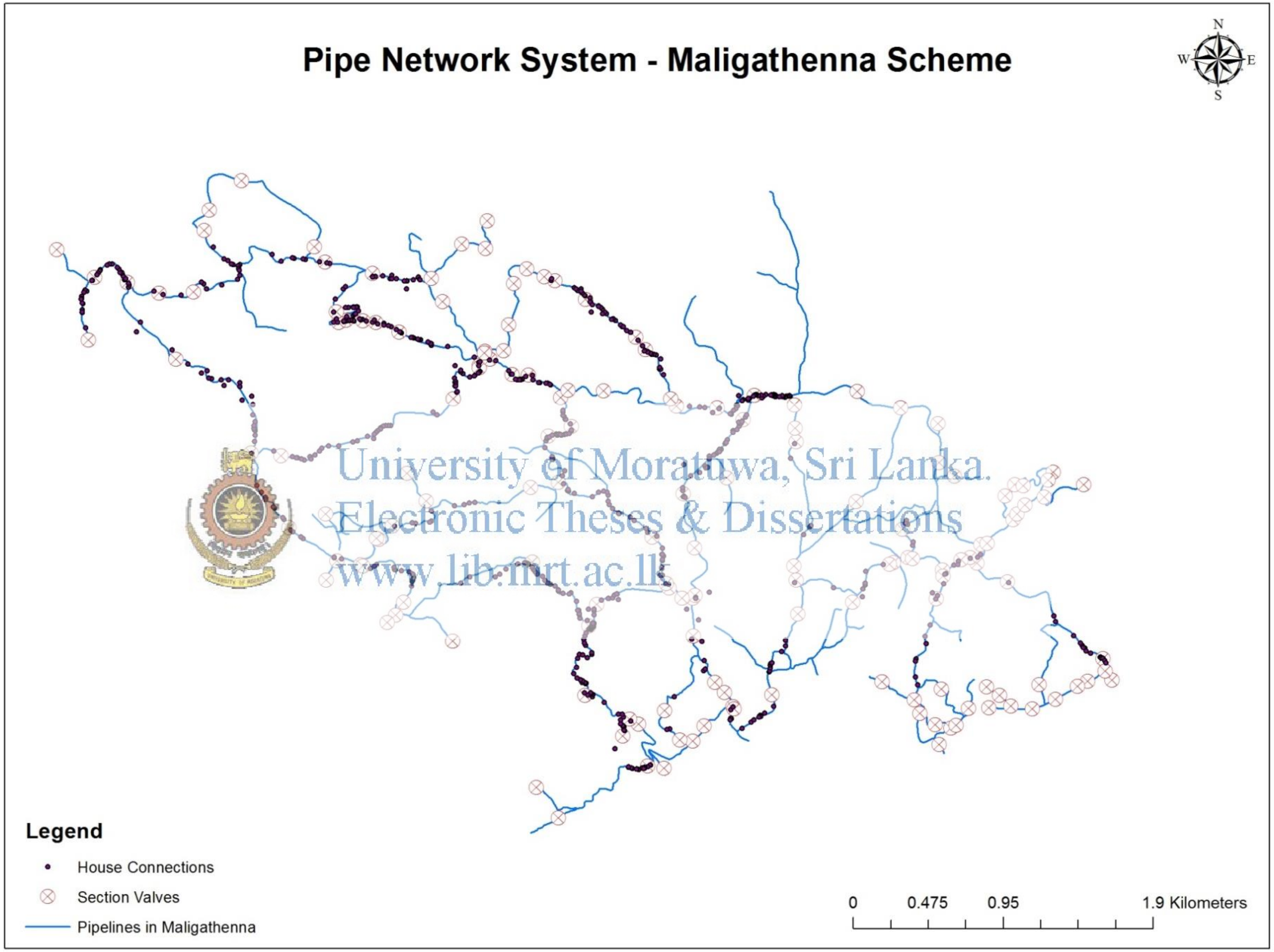


Figure 4.1: Pipe network system of Maligathenna Scheme

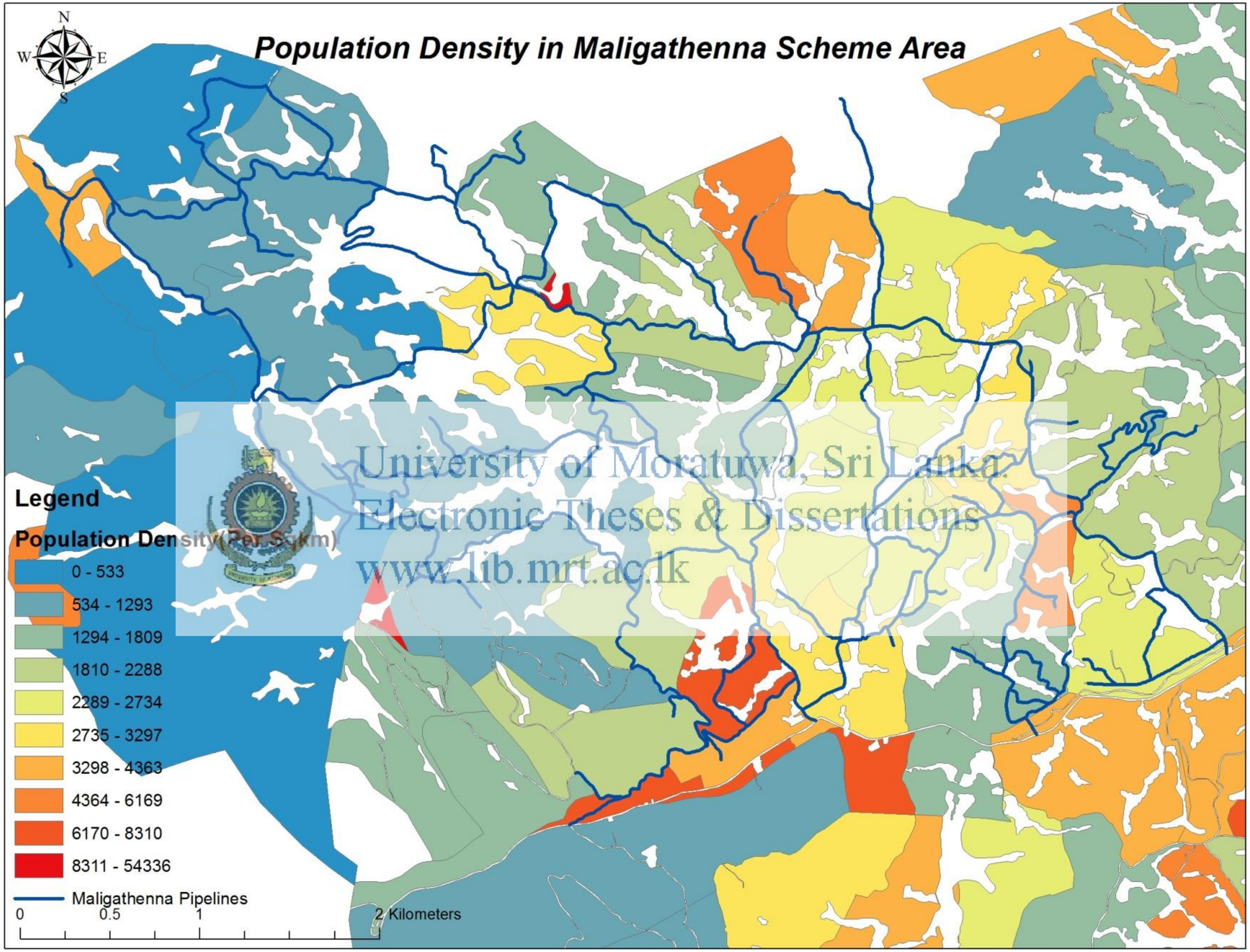


Figure 4.2: The pipe network superimposed on the population density map of Maligathenna Area

4.3 Results, Analysis and discussion of field data, model data and laboratory investigated data

The analysis aims at interpreting RCl, THM, TOC, Pressure, Water age, Turbidity and Conductivity data.

4.3.1 Residual Chlorine

Table 4.1: RCl values of different sampling locations in Kandy South Region

Address	RCl mg/l
Malwatta Estate,Arambegama,Pilimathalawa	0.35
192,Kudaoya,Pilimatalawa	0.35
Giragama estate, Pilimatalawa	0.00
91/1,Urapola,Kudaoya,Pilimatalawa	0.45
Kuruduwatta,Pilimatalawa	0.50
Kotabogoda,Kuruduwatta , Pilimatalawa	0.50
Kotabogoda , Kadugannawa	0.20
5b3,Siyabalagoda,Danthure	0.40
Sinhagiri hotel,Danture	0.10
Walgampaya,Danture	0.10
Doluwagama,Domgaspitiya,Menikdiwela	0.20
317a,Rahthepitiya Junction,Menikdiwela	0.40
Hansawila,Menikdiwela	0.10
Udarathmeewana,Menikdiwela	0.20
193,Nagahapitiya,Walgowwagoda,Danture	0.50
233, Kandangama,Kadugannawa	0.15
117a,Naththaranpotha, Ketakumbura	0.50
Wikum,Mamudawala,Ketakumbura	0.10
132/3,Walgowwagoda,Danture	0.20
64,Walgowwagoda ,Danture	0.40
School Junction, Menikdiwela	0.00
181/1, Galanga, Manikdiwela	0.00
Ketakumbura, Kadugannawa	0.00
48c, Liyanage, Maligathenna, Ketakumbura	0.00
325, Kandy road, Kadugannawa	0.00
163 Gampola Road Kadugannawa	0.00
Construction site, 21, Danture Road.Pilimatalawa	0.00
270, Nugamadda, Bathgodapitiya, Manikdiwela	0.00
Jayalath, 331, Siyambalagedara, Danture	0.00
Mlesna Tea Center, 445, Kiribathkumbura	0.00
Kurunduwatta, Meewathura	0.20
173,Udalotuwwa,Aththaragama,Handessa	0.10
Naranwela, Handessa	0.00

76/B, Elugoda, Peradeniya	0.00
190,Parana Gampola Road,Peradeniya	0.00
Galbangalawa ,UOP	0.65
Rest house, Mahakanda	0.50
Service Reservoir-Mahakanda	0.60
CB Ratnayaka, Kanhiya road, Mahakanda, Sarasavigama	0.50
Address not available	0.30
Fathers House , Mahakanda	0.35
Address not available	0.30
108, Galaha Road, Hindagala	0.50
36, Galaha Road	0.70
University of Peradeniya,Hostal	0.90
University of Peradeniya,Hostal	0.40
University of Peradeniya,Science Faculty	0.90
Meewathura Treatment Plant	0.60
University Treatment Plant	1.10

Referring to the table 4.1, RCl variation throughout the Kandy South Region varies in a wide range. The Meewathura Treatment Plant maintains a high RCl value of 0.6mg/l in their final treated water, while University Treatment Plant maintains a higher RCl value as high as 1.1mg/l. During the distribution phase the minimum recommended value of RCl is 0.2mg/l and the maximum value is 1mg/l, which is not maintained at most of the locations. From the total sampling locations only 58% were having the 0.2mg/l or higher RCl value. The most significant finding here was that RCl value was nil at 30% of samples where most of those points were at the outskirt of the pipe distribution network.

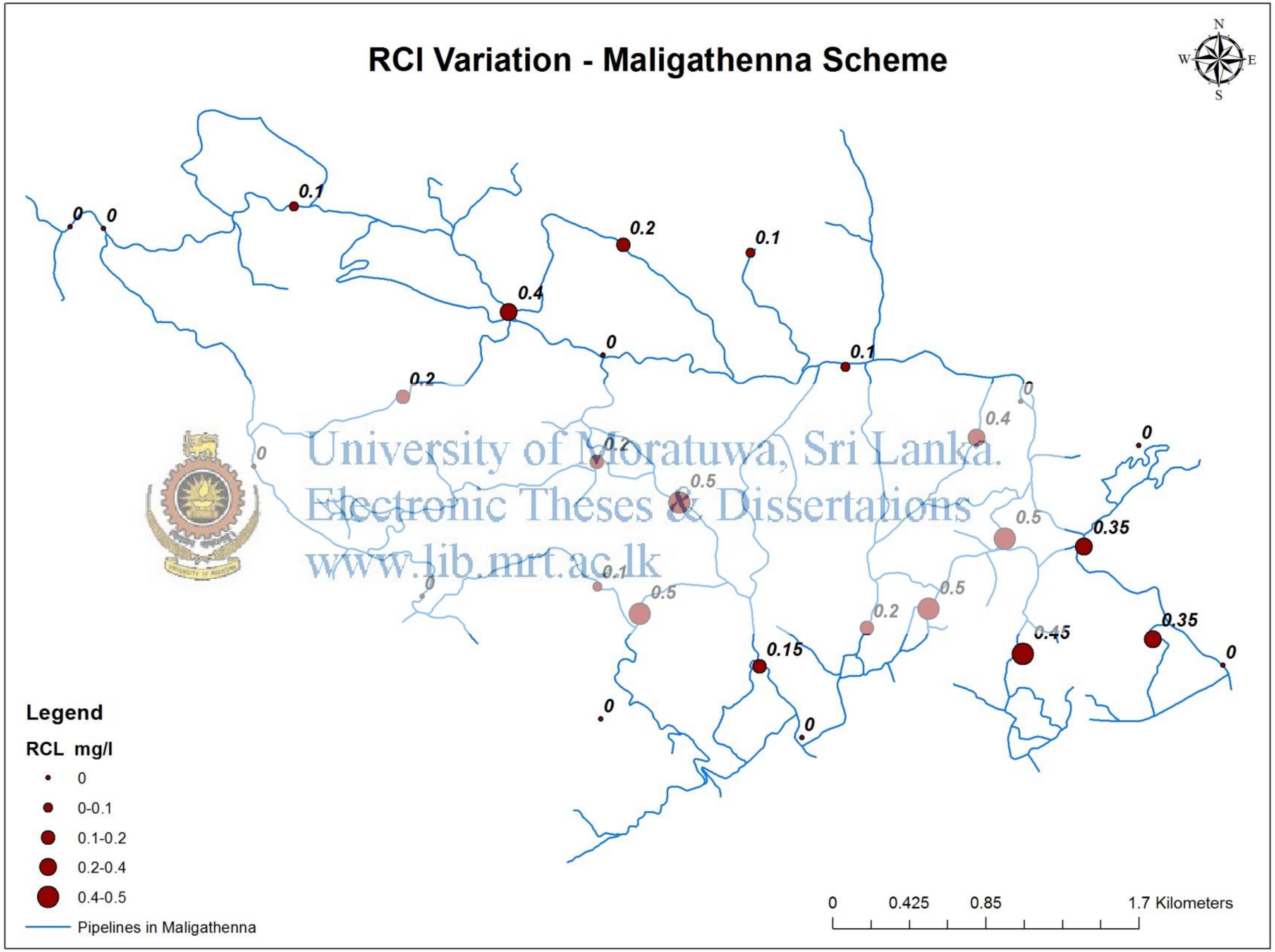


Figure 4.3: RCl variation in Maligathenna Scheme

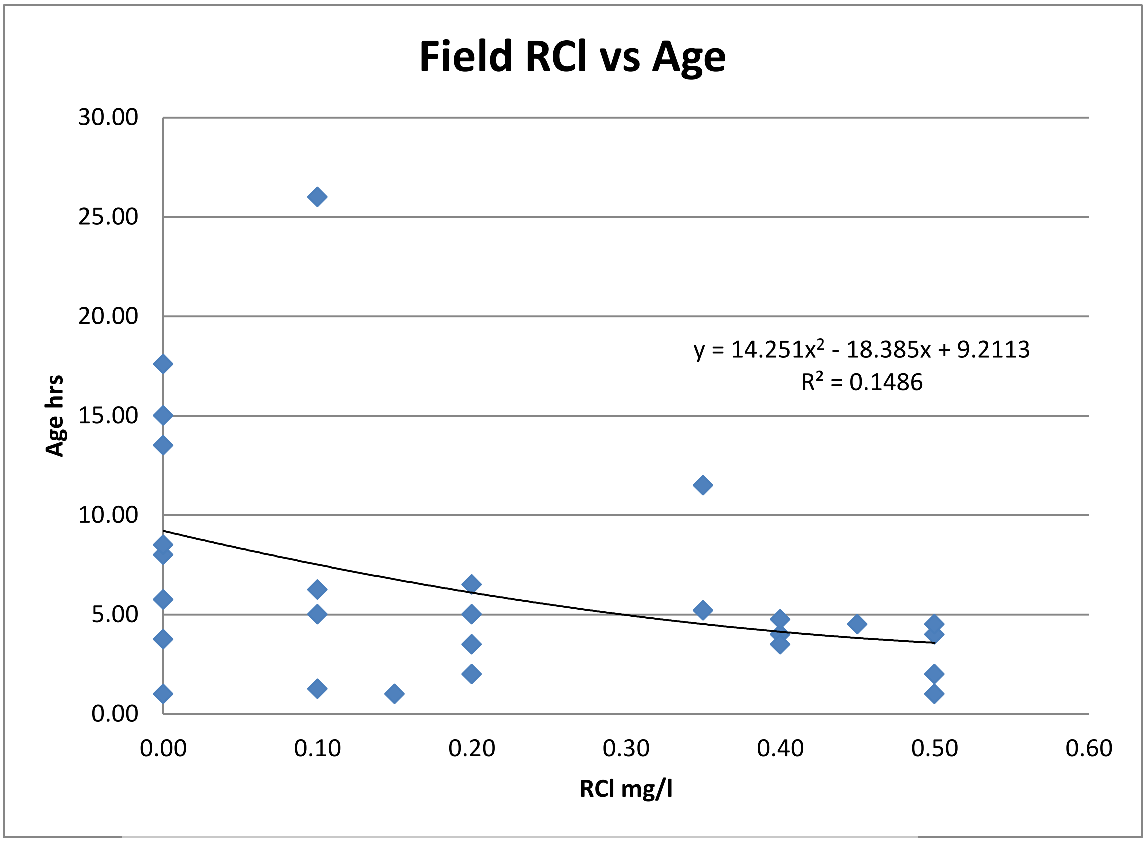


Figure 4.4: Residual Chlorine variation with Water Age

There could be several reasons behind this scenario. Referring to figure 4.4, RCl decay with the age of water in pipelines, but all these RCl nil locations were not having longer retention time. Therefore the contamination may take place somewhere in the distribution system or in the storage tank. The generally accepted principle in drinking water systems is to maintain a closed surrounding for storing and transporting water from treatment plant to customer's tap. Any violation to that norm will create a potential of contamination. As described in the methodology this is a hilly area having break pressure tanks in the distribution system. Water could get contaminated in such places since the maintenance work seems to be unsatisfactory. There were some poor performing valves in several locations of the distribution system. In addition there could be unidentified cross connections in the distribution system. Further the storage tank was having a risk of contamination from ingress of environmental pollutants or faecal contamination from animals, birds and insects.

The deterioration of residual chlorine is also caused by the formation of DBPs. As such the free chlorine might have been converted to THM, so that the RCl value decreases. Considering these scenarios, there is a very high risk of water getting polluted biologically by pathogenic microorganisms. Microorganisms that grow in the environment may enter the drinking-water distribution system and attach to and grow on drinking-water pipes and other surfaces, forming biofilms.

Excessive RCl values were observed in several sampling points, where the majority of such locations are fed by University Treatment Plant. An excessive chlorine amount is added to the final water which is released from treatment plant. This is also harmful to consumers as well as the pipe distribution system. As per the observations made during this study, the presence of TTHM is prominent in high RCl points. (Refer table 4.2). That highlights the formation of DBP which are harmful to consumer's health. On the other hand high content of free chlorine creates a higher acidity level in water, thus induce the iron corrosion (Pisigan & Singley, 1987; Cantor, Park & Vaiyavatjamai, 2000).

Table 4.2: Sampling points with higher TTHM and higher RCl

Address	**TTHM ppb**	**RCl mg/l**
Galbangalawa,UOP	38.247	0.65
Rest house,Mahakanda	14.256	0.50
Service Reservoir-Mahakanda	23.668	0.60
CB Rathnayaka,Kanhiya Road,Mahakanda	20.433	0.50
Address not available	7.743	0.30
Fathers House,Mahakanda	21.613	0.35
Address not available	19.619	0.30
108,Galaha Road,Hindagala	18.505	0.50
36,Galaha Road	18.247	0.70
University of Peradeniya,Hostal	28.610	0.90
University of Peradeniya,Hostal	19.692	0.40
University of Peradeniya,Science Faculty	17.644	0.90
Meewathura Treatment Plant	17.496	0.60
University Treatment Plant	19.384	1.10

NWSDB is currently suffering from NRW figure of around 23.6% in Central Province. This is comparatively a very high figure compared to developed countries like Singapore, Canada which are having around 5% of NRW. That means our systems are highly vulnerable for frequent leakages and pipe bursts. The leakages which are not visible are very dangerous because nobody knows the extent of the hazard brought in to the system. Therefore maintaining a sufficient residual protection in the system is utmost important to ensure the safety of water.

As per the water safety plan it is a hazard associated with the distribution system (Module 03 of WSP manual). This risk is not identified by the responsible NWSDB officers in the area; hence it could lead to a presence of a hazard. Therefore this is an occurrence of a Hazardous Event as described in the water safety plan manual, a possible situation where the loss of water quality integrity could occur. Incompetence of the existing chlorination system is the main reason for all these highlighted risks prevailing in the system. Hence suitable modifications should be introduced in order to achieve a better water quality.

However, according to the regional laboratory data a significant microbiological contamination is not highlighted. These samples were collected covering entire Maligathenna scheme during the same hour of the day as we carried out our sampling work. The locations were not exactly the same locations we referred, but were located close-by. It appears that bacterial recontamination has not taken place in the pipe system in this instance, even though there is a risk due to the absence of residual chlorine.

Table 4.3: Regional laboratory microbiological test data

Address	**Coliform**	**E-Coli**
Mrs, R.L. Kusumawathi, No:02, Panabokka	0	0
Mr, Ranjith Premakumara, No:42 B, Ketakumbara	0	0
Mr, Thilak Dedunupitiya, No:110, Ketakumbura	0	0
Mr, J.M.Ghani, No:272 A, Kurukuththala	0	0
Mr, M.Ramzeen, No:306 B -2, Kurukuththala	0	0
Mr, M.Kristi, Kurukuththala	0	0
District Hospital, Kadugannawa	0	0
Lagamuwa Post Office, Lagamuwa	0	0
Hotel Milan, Kadugannawa	0	0
French Bekary, Muruthalawa	0	0
Mr,W. G. Wimalasiri, Pilapitiya	0	0
Sudharmaramaya, Puwakgahapitiya, Muruthalawa	0	0

Analysis of RCl field data and water quality model data

A water quality model was developed using Bentley WaterGEMS software. The analysis was carried out for both present and future demands of the Maligathenna scheme.

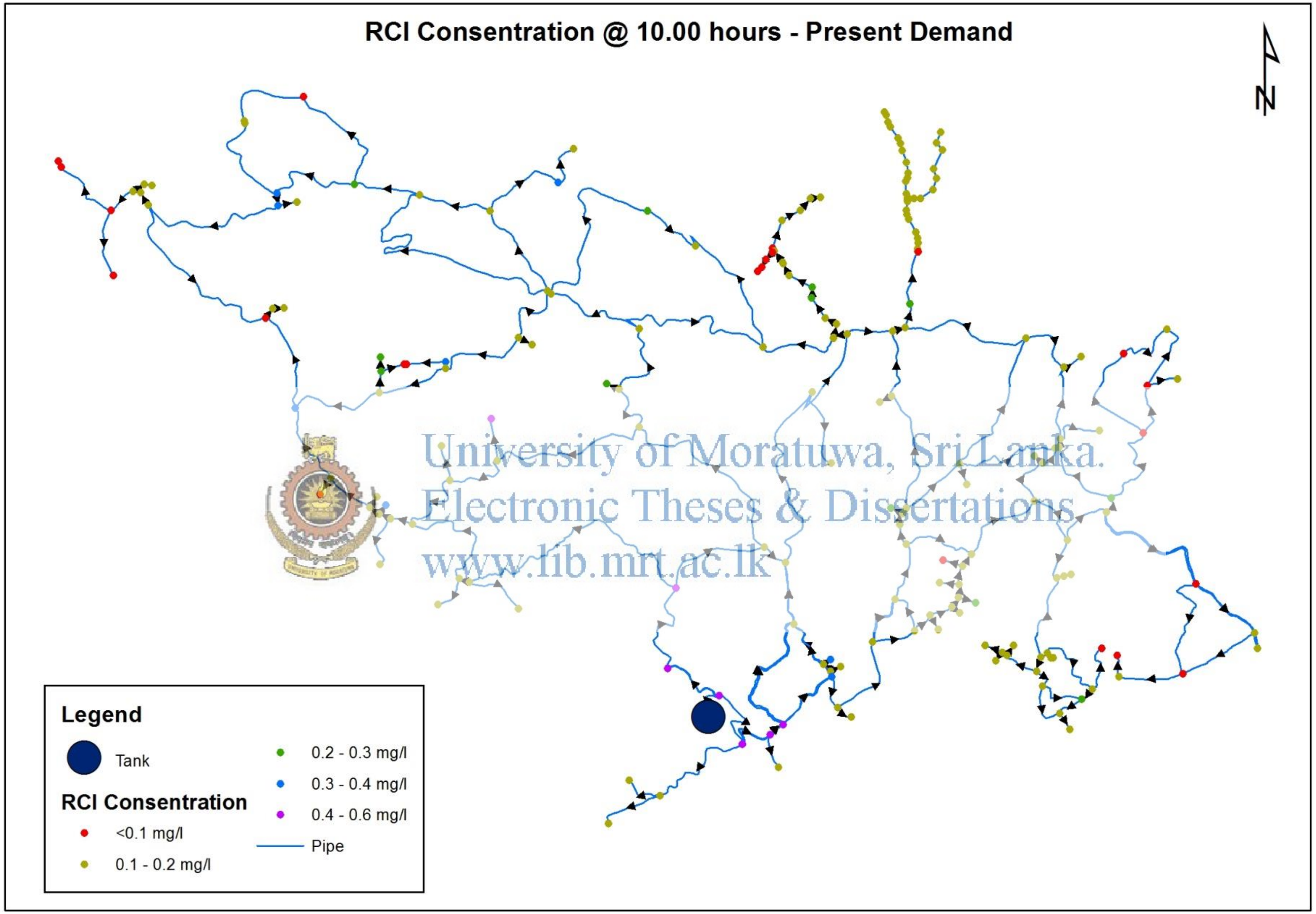


Figure 4.5: Water Quality model for Maligathenna scheme under present demand – Residual Chlorine

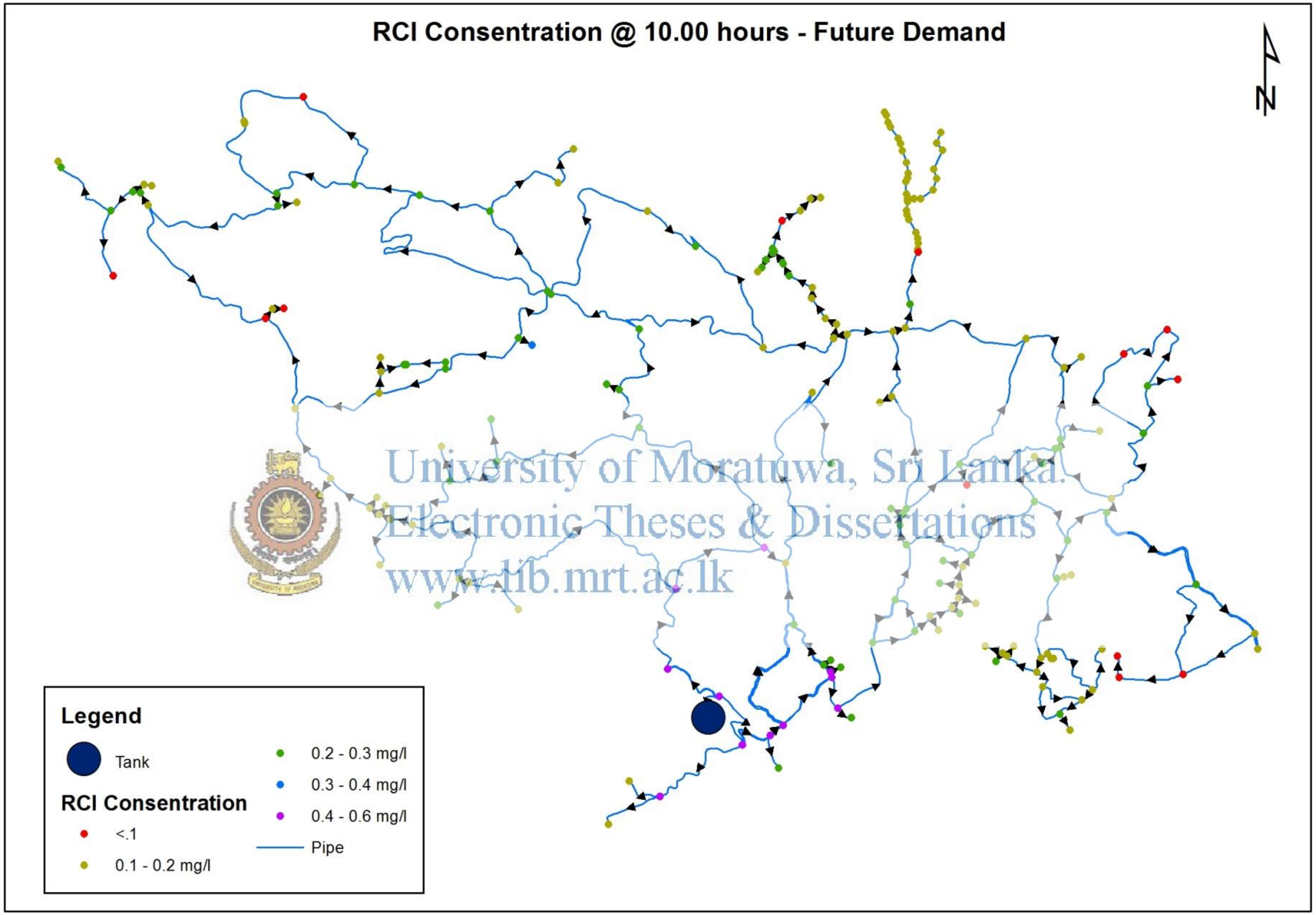


Figure 4.6: Water Quality model for Maligathenna scheme under future demand – Residual Chlorine

Table 4.4: Field RCl values and model RCl values

Sample No	Field RCl mg/l	Model RCl mg/l (Present demand)	Model RCl mg/l (Future demand)
1	0.35	0.2	0.2
2	0.35	0.14	0.29
3	0.00	0.06	0.23
4	0.45	0.14	0.4
5	0.50	0.37	0.47
6	0.50	0.15	0.2
7	0.20	0.5	0.52
8	0.40	0.37	0.4
9	0.10	0.12	0.25
10	0.10	0.03	0.09
11	0.20	0.12	0.2
12	0.40	0.16	0.45
13	0.10	0.13	0.2
14	0.20	0.15	0.22
15	0.50	0.5	0.45
16	0.15	0.44	0.44
17	0.50	0.2	0.3
18	0.10	0.2	0.26
19	0.20	0.17	0.53
20	0.40	0.3	0.4
21	0.00	0.21	0.2
22	0.00	0.13	0.2
23	0.00	0.45	0.49
25	0.00	0.52	0.33
27	0.00	0.08	0.21
28	0.00	0.17	0.5
29	0.00	0.12	0.16
30	0.00	0.25	0.2

Observed values of RCl at the field were compared with the model RCl values by plotting against each. A significantly good co-relation was observed between those two parameters.(figure 4.7) Hence it could be assumed that the water quality model is satisfactorily calibrated and realistic in predicting water quality parameters (RCl, Age). Complying with the WSP risk assessment approach, this is a very good approach for identifying the potentially low RCl and excessive RCl to assess the risks. Referring to figure 4.5, red color areas are having insufficient RCl levels. In addition future threats to the system also could be identified using the water quality model developed using future demand of the area. (Figure 4.6)

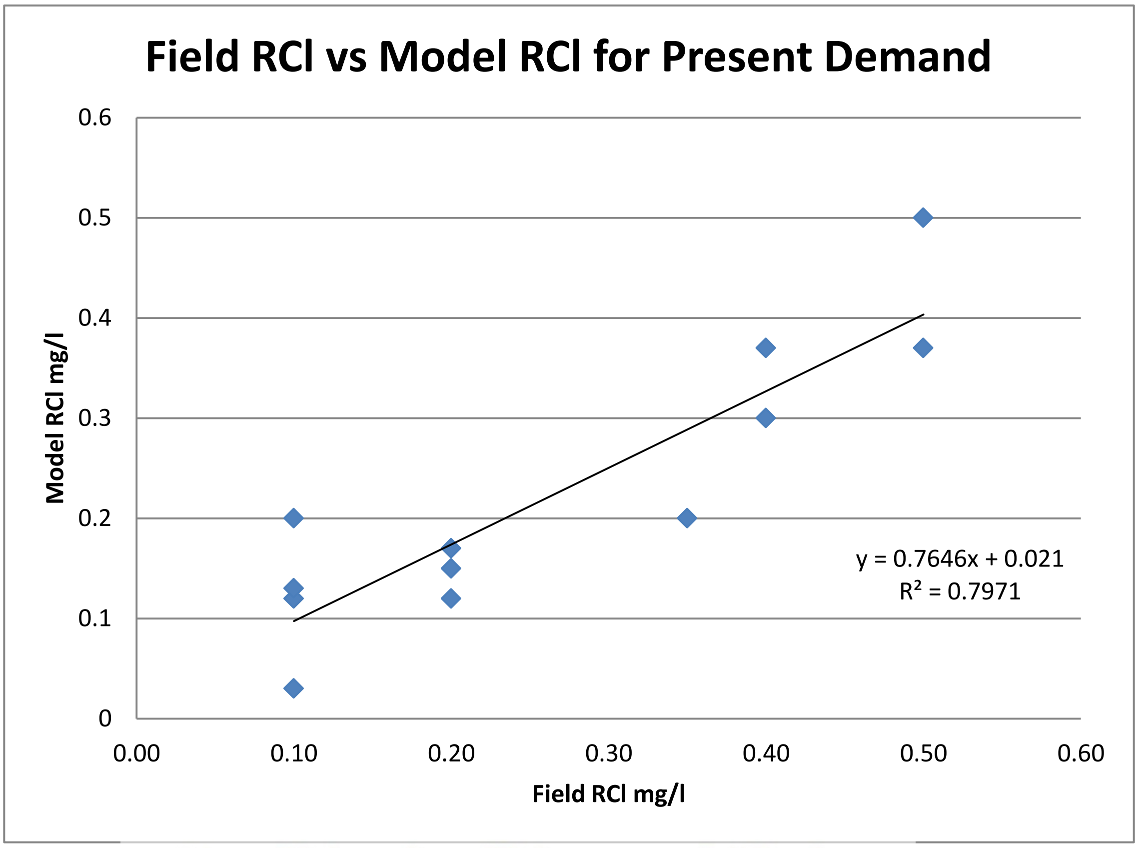


Figure 4.7: Plot of field RCl vs Model RCl for present demand

4.3.2 Total Trihalomethane

Table 4.5: TTHM values of different sampling locations in Kandy South Region

Address	TTHM ppb
Malwatta Estate,Arambegama,Pilimathalawa	0.000
192,Kudaoya,Pilimatalawa	0.000
Giragama Estate,Pilimatalawa	0.000
91/1,Urapola,Kudaoya,Pilimatalawa	0.000
Kuruduwatta,Pilimatalawa	0.000
Kotabogoda,Kuruduwatta,Pilimatalawa	0.000
Kotabogoda ,Kadugannawa	0.000
5b3,Siyabalagoda,Danture	0.000
Sinhagiri hotel,Danture	0.000
Walgampaya,Danture	0.000
Doluwagama,Domgaspitiya,Menikdiwela	0.000
317a,Rahthepitiya Junction ,Menikdiwela	0.000
Hansawila,Menikdiwela	0.000
Udarathmeewana,Menikdiwela	0.000
193,Nagahapitiya,Walgowwagoda,Danture	9.720
233, Kandangama,Kadugannawa	0.000
117a,Naththaranpotha,Ketakumbura	0.000

Wikum,Mamudawala,Ketakumbura	0.000
132/3,Walgowwagoda,Danture	0.000
64,Walgowwagoda,Danture	0.000
School Junction,Menikdiwela	9.699
Poththapitiya Bakery	16.426
181/1, Galanga,Manikdiwela	10.200
Ketakumbura,Kadugannawa	0.000
48c, Liyanage,Maligathanna,Ketakumbura	11.120
325, Kandy road,Kadugannawa	9.753
163,Gampola Road,Kadugannawa	9.364
Construction site,21,Danture road,Pilimatalawa	8.493
270,Nugamadda,Bathgodapitiya,Menikdiwela	8.601
Jayalath,No.331,Siyambalagedara,Danture	1.182
Melesna Tea Center,No.445,Kiribathkumbura	0.150
Kurunduwatta,Meewathura	8.317
173,Udalotuwwa,Aththaragama,Handessa	8.372
Naranwela,Handessa	0.000
76/B, Elugoda,Peradeniya	0.000
190,Parana Gampola Road,Peradeniya	0.000
Galbangalawa,UOP	38.247
Rest house,Mahakanda	14.256
Service Reservoir-Mahakanda	23.668
CB Rathnayaka,Kanhiya road,Mahakanda,Sarasavigama	20.433
Address not available	7.743
Fathers House ,Mahakanda	21.613
Address not available	19.619
108,Galaha Road,Hindagala	18.505
36,Galaha Road	18.247
University of Peradeniya,Hostal	28.610
University of Peradeniya,Hostal	19.692
University of Peradeniya,Science Faculty	17.644
Meewathura Treatment Plant	17.496
University Treatment Plant	19.384

TTHM was present at more than 50% of sampling locations and were quite high in extreme points of pipe distribution system. Out of the four types of THM species only two types were present in the tested samples. Those are Trichloromethane (TCM) and Bromodichloromethane (BDCM). However there is a doubt about the validity of some of this "*zero TTHM"* locations because the samples were collected just after a sudden water interruption of 10 hours in that area. The formation of THM is supposed to be associated with water age; hence most probably there could be a certain positive value of TTHM in those locations under normal conditions of regular supply. Schemes which were on right bank side of Mahaweli River were mostly present with high TTHM concentrations. Since there are no Sri Lankan Standards specified for the maximum permissible level for TTHM, USEPA or any other national standard (such as Netherlands, Germany, Sweden etc.) have to be adopted. The concentrations are quite alarming at some locations because those values exceed the maximum permissible values stipulated in certain standards of some other countries. (Netherlands 1ppb, Germany 10ppb, Sweden 20ppb, USEPA 80ppb). In that respect some segments of the distribution system are in risk.

The reasons could be the longer retention time of water inside the distribution system. A water quality model was developed to analyze the water age of the distribution system. Further the THM formation may also be caused by the presence of high RCl values and organic content within the distribution system.

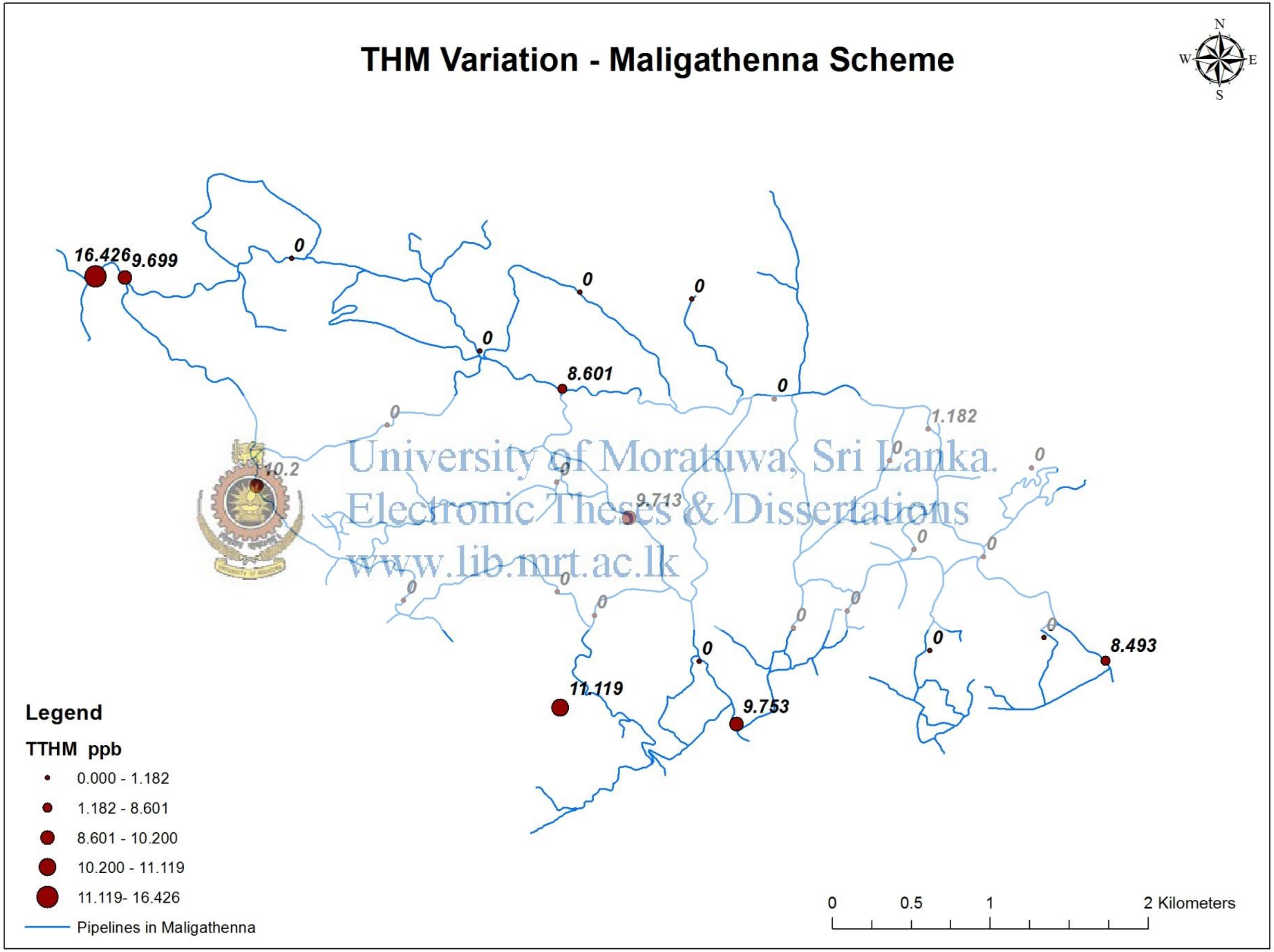


Figure 4.8: TTHM variation in Maligathenna scheme

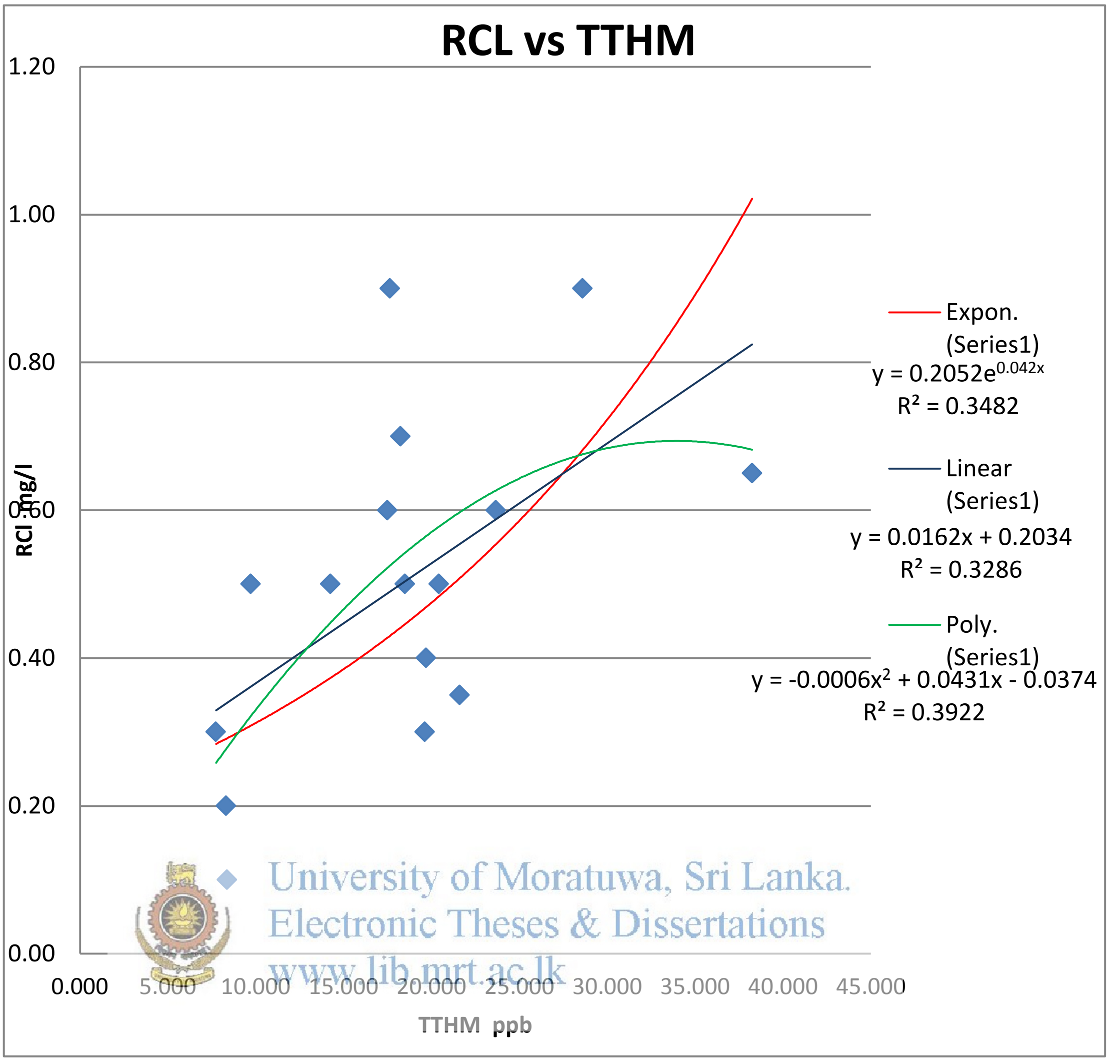


Figure 4.9: Co-relation between TTHM and RCl

As shown in the above figure 4.9, there exists a positive relationship between RCl and TTHM. Data were plotted and the trend lines were developed to see the linear, polynomial and exponential relationships between the two parameters. Best relationship was observed in the polynomial trend line where R^2 value was around 0.4. A higher significant relationship could be achieved if more data is available and in addition if the data is analyzed using artificial neural network (ANN) technique.

4.3.3 Total Organic Carbon, Turbidity, Conductivity

Table 4.6: TOC, Turbidity, Conductivity values of different sampling locations in Kandy South Region

Address	TOC mg/l	Turbidity NTU	Conductivity µS/cm
Malwatta Estate,Arambegama,Pilimatalawa	0.381	0.18	118.80
192, Kudaoya, Pilimatalawa	0.951	0.42	86.80
Giragama Estate, Pilimatalawa	0.787	0.24	174.00
91/1, Urapola, Kudaoya, Pilimatalawa	1.413	0.35	87.00
Kuruduwatta, Pilimatalawa	0.895	0.42	86.10
Kotabogoda, Kuruduwatta,Pilimatalawa	0.577	0.37	87.30
Kotabogoda , Kadugannawa	0.734	0.36	87.70
5b3, Siyabalagoda, Danture	7.649	0.25	81.50
Sinhagiri hotel,Danture	1.410	0.25	82.80
Walgampaya,Danture	2.164	0.54	87.10
Doluwagama, Domgaspitiya, Menikdiwela	0.477	0.75	81.00
317a, Rahthepitiya Junction, Menikdiwela	1.042	0.29	85.20
Hansawila, Menikdiwela	1.006	0.29	86.10
Udarathmeewana, Menikdiwela	2.605	0.45	86.20
193, Nagahapitiya, Walgowwagoda, Danture	1.075	0.41	87.30
233, Kandangama, Kadugannawa	1.760	0.25	82.90
117a, Naththaranpotha, Ketakumbura	1.151	0.14	82.00
Wikum, Mamudawala, Ketakumbura	0.517	1.34	86.60
132/3, Walgowwagoda, Danture	2.857	0.36	78.40
64, Walgowwagoda, Danture	1.986	N/A	N/A
School Junction, Menikdiwela	2.257	0.16	66.90
Poththapitiya Bakery	1.136	0.43	76.80
181/1, Galanga, Manikdiwela	1.292	0.24	69.70
Ketakumbura,Kadugannawa	0.819	0.14	69.60
48c, Liyanage, Maligathanna, Ketakumbura	2.790	0.21	74.10
325, Kandy Road, Kadugannawa	1.451	0.85	70.40
163, Gampola Road, Kadugannawa	2.850	0.10	71.70
Construction site,21, Danture Road, Pilimatalawa	0.443	0.09	82.70
270,Nugamadda,Bathgodapitiya,Menikdiwela	2.084	0.33	70.80
Jayalath, No.331, Siyambalagedara, Danture	1.104	0.20	71.00
Mlesna Tea Center, No.445,Kiribathkumbura	0.710	0.35	73.60
Kurunduwatta,Meewathura	0.745	0.11	76.30
173, Udalotuwwa,Aththaragama,Handessa	1.314	0.15	73.70
Naranwela, Handessa	1.487	0.65	89.60
76/B, Elugoda, Peradeniya	1.082	0.55	123.20
190, Parana Gampola Road, Peradeniya	0.929	0.67	93.60

N/A – Not available

Referring to figure 4.10, TOC values were scattered in a wide range from 0.381 to 7.649mg/l. TOC results for treated water should generally not exceed 2.0 mg/L. At TOC >4.0 mg/l it is likely that THM levels will exceed 100 µg/l if the residence time in the network is 2-3 days and if a free residual chlorine is to be maintained at the tap (UKWIR, 2000). However, EPA guidelines indicate that THM formation can occur at levels below this in some circumstances (>2.0 mg/l). Therefore, if the levels of TOC are greater than 4.0 mg/l remedial works will likely be necessary, whereas if the level is between 2 and 4 mg/l a more detailed assessment will need to be carried out to determine if these levels of TOC are leading to the formation of THMs. In this set of data 8 sampling locations (22% of total points) were having the TOC level exceeding 2 mg/l. Hence the system is vulnerable for the formation of THM.

Turbidity is a measure of suspended solids or the cloudiness in water. The maximum desirable level of turbidity is 2 NTU and maximum permissible level is 8 NTU as per the SLS standards. Results of all the sampling locations were complying that limit, hence there is no risk involved in that respect.(figure 4.11) However WHO establishes that the turbidity of drinking water shouldn't be more than 5 NTU, and should ideally be below 1 NTU. One of our sampling locations exceeds 1 NTU hence system is not in the ideal condition. However when referring to the past recorded laboratory test data of this scheme it was observed that in certain days turbidity values were in the range of 60NTU. Even though those data are not referred in this study there will be certain situations where the risk of high turbidity could prevail. Turbidity can serve to signal potential contamination problems or difficulties within a distribution system. Increased distribution system turbidity can be indicative of breaches to the distribution system integrity, such as main breaks, backflow, intrusions, cross connections or detachment of biofilm, which may compromise the microbiological quality of the water (Kirmeyer et al., 2000). Turbidity may also increase due to hydrant opening, system maintenance and repairs, and valve failures. Increased turbidity has also been associated with the release of corrosion products or disturbances of deposits (USEPA, 2006d). Discolored drinking water in the distribution system is often attributed to the presence of colloidal and particulate iron which can originate from both distribution system materials and source water (Schock and Lytle, 2011). If high turbidity is detected, necessary remedial actions should be taken to undertake water main flushing until normal turbidity levels restored.

Conductivity in water is affected by the presence of inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions (ions that carry a negative charge) or sodium, magnesium, calcium, iron, and aluminum cations (ions that carry a positive charge). Organic compounds like oil, phenol, alcohol, and sugar do not conduct electrical current very well and therefore have a low conductivity when in water. Conductivity is also affected by temperature: the warmer the water, the higher the conductivity. Maximum desirable level is specified as 750µS/cm as per the SLS standards and 3500µS/cm is the maximum permissible level. When reviewing the collected data all our sampling locations were within that limit. Few points deviated significantly from the average, the reason supposed to be was that those points were in far ends of distribution system hence there is a potential of contamination and corrosion of pipe material. (Refer figure 4.12)

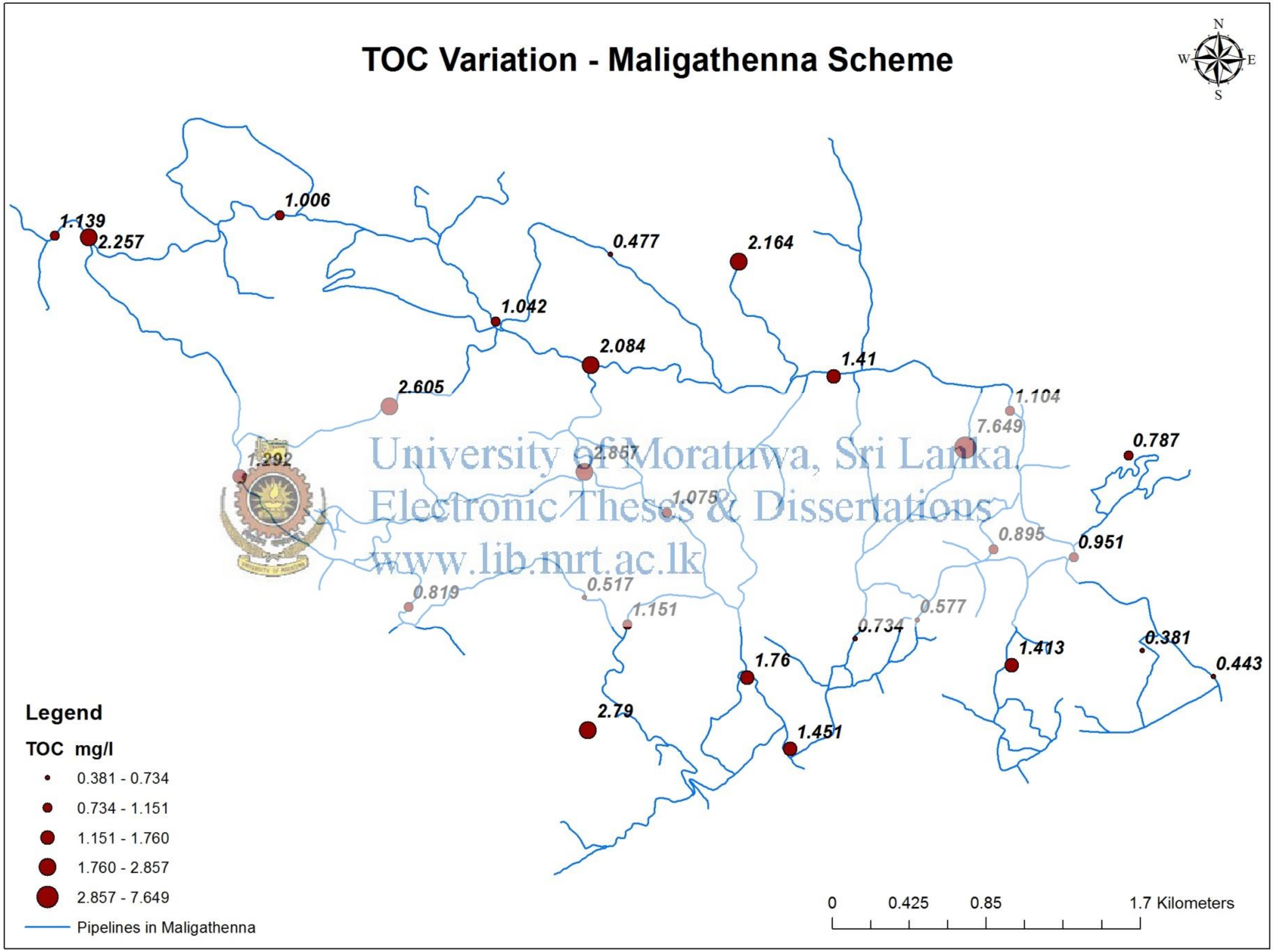


Figure 4.10: Total organic carbon variation in Maligathenna scheme

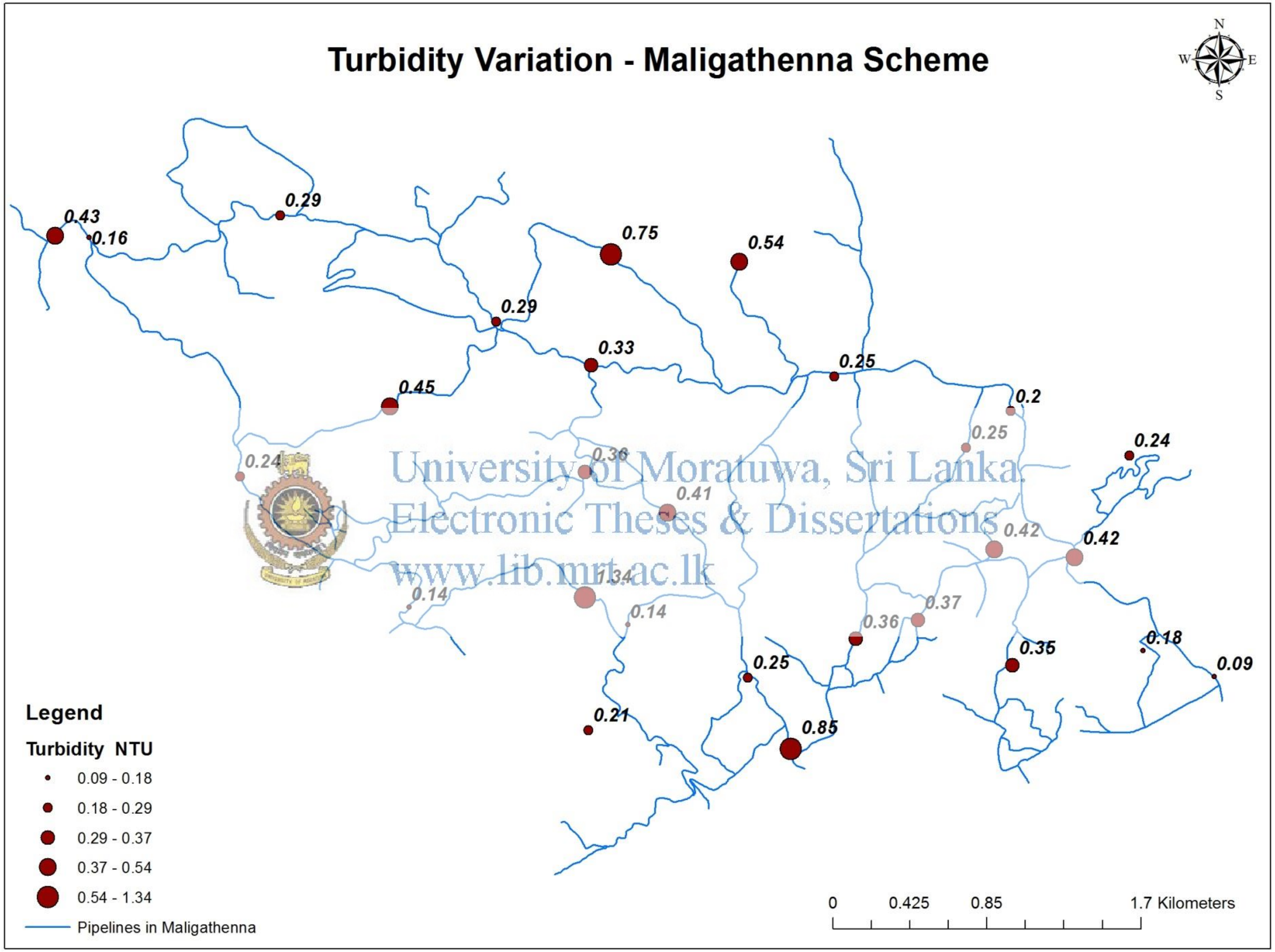


Figure 4.11: Turbidity variation in Maligathenna scheme

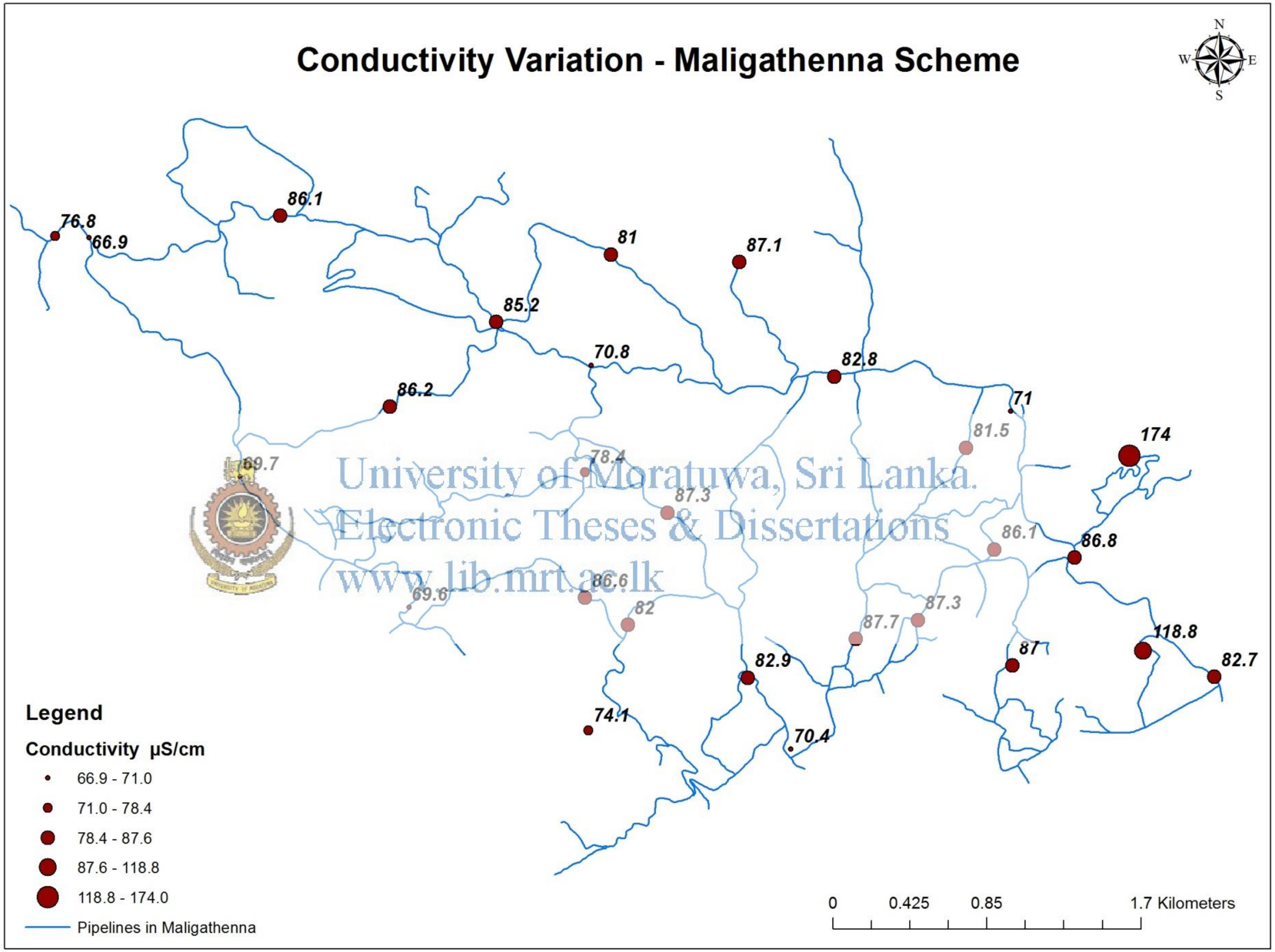


Figure 4.12: Conductivity variation in Maligathenna scheme

4.3.4 Results of hydraulic model

Table 4.7: Pressure and age values of Maligathenna scheme

Address	Pressure at 1000hrs bars	Age under present demand hours	Age under future demand hours
Malwatta Estate,Arambegama,Pilimatalawa	8.80	11.50	7
192,Kudaoya,Pilimatalawa	8.40	5.20	4.5
Giragama Estate,Pilimatalawa	7.16	17.60	14.5
91/1,Urapola,Kudaoya,Pilimatalawa	7.61	4.50	3.5
Kuruduwatta,Pilimatalawa	6.70	4.00	3
Kotabogoda,Kuruduwatta,Pilimatalawa	4.80	4.50	3.5
Kotabogoda ,Kadugannawa	7.43	2.00	1.5
5b3,Siyabalagoda,Danture	7.80	4.00	3.75
Sinhagiri hotel,Danture	7.80	5.00	4
Walgampaya,Danture	1.19	26.00	21
Doluwagama,Domgaspitiya,Menikdiwela	3.32	6.50	5.5
317a,Rahthepitiya Junction,Menikdiwela	6.25	4.75	4
Hansawila,Menikdiwela	4.00	6.25	5
Udarathmeewana,Menikdiwela	6.80	5.00	4.5
193,Nagahapitiya,Walgowwagoda,Danture	7.56	2.00	1.25
233,Kandangama,Kadugannawa	8.98	1.00	0.75
117a,Naththaranpotha,Ketakumbura	6.54	1.00	0.63
Wikum,Mamudawala,Ketakumbura	6.10	1.25	1
132/3,Walgowwagoda,Danture	4.44	3.50	2.5
64,Walgowwagoda,Danture	7.37	3.50	2.5
School Junction,Menikdiwela	4.53	8.00	6
Poththapitiya Bakery	6.16	8.50	6.25
181/1,Galanga,Manikdiwela	6.02	5.75	4.75
325,Kandy Road,Kadugannawa	5.32	1.00	0.8
Ketakumbura,Kadugannawa	9.23	4	3
Construction site,21,Danture Road,Pilimatalawa	5.97	15.00	10.75
270,Nugamadda,Bathgodapitiya,Menikdiwela	6.65	3.75	2.5
331,Siyabalagedara,Danture	6.9	6.25	5

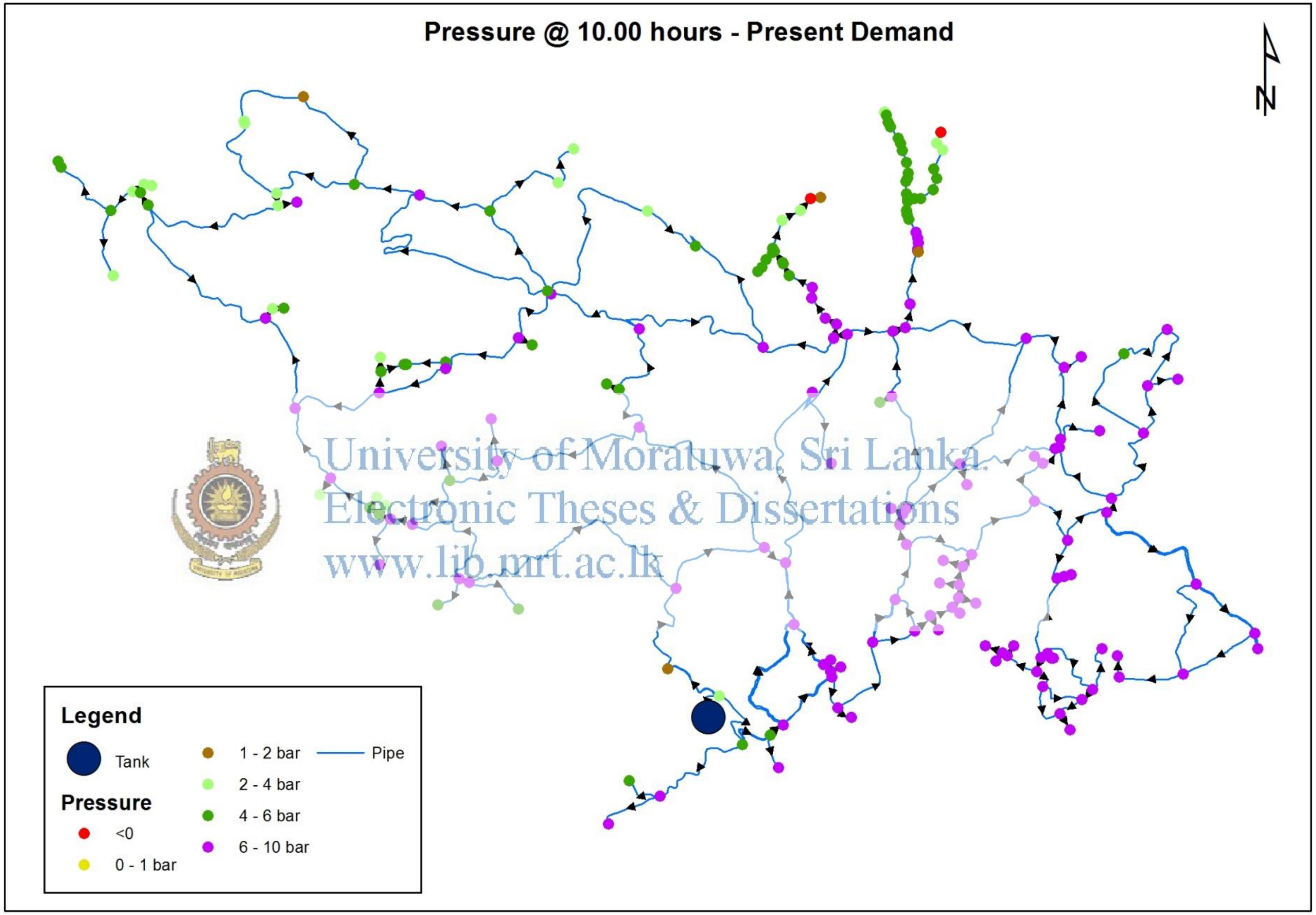


Figure 4.13: Pressure variation of Maligathenna scheme at 1000 hours under present demand

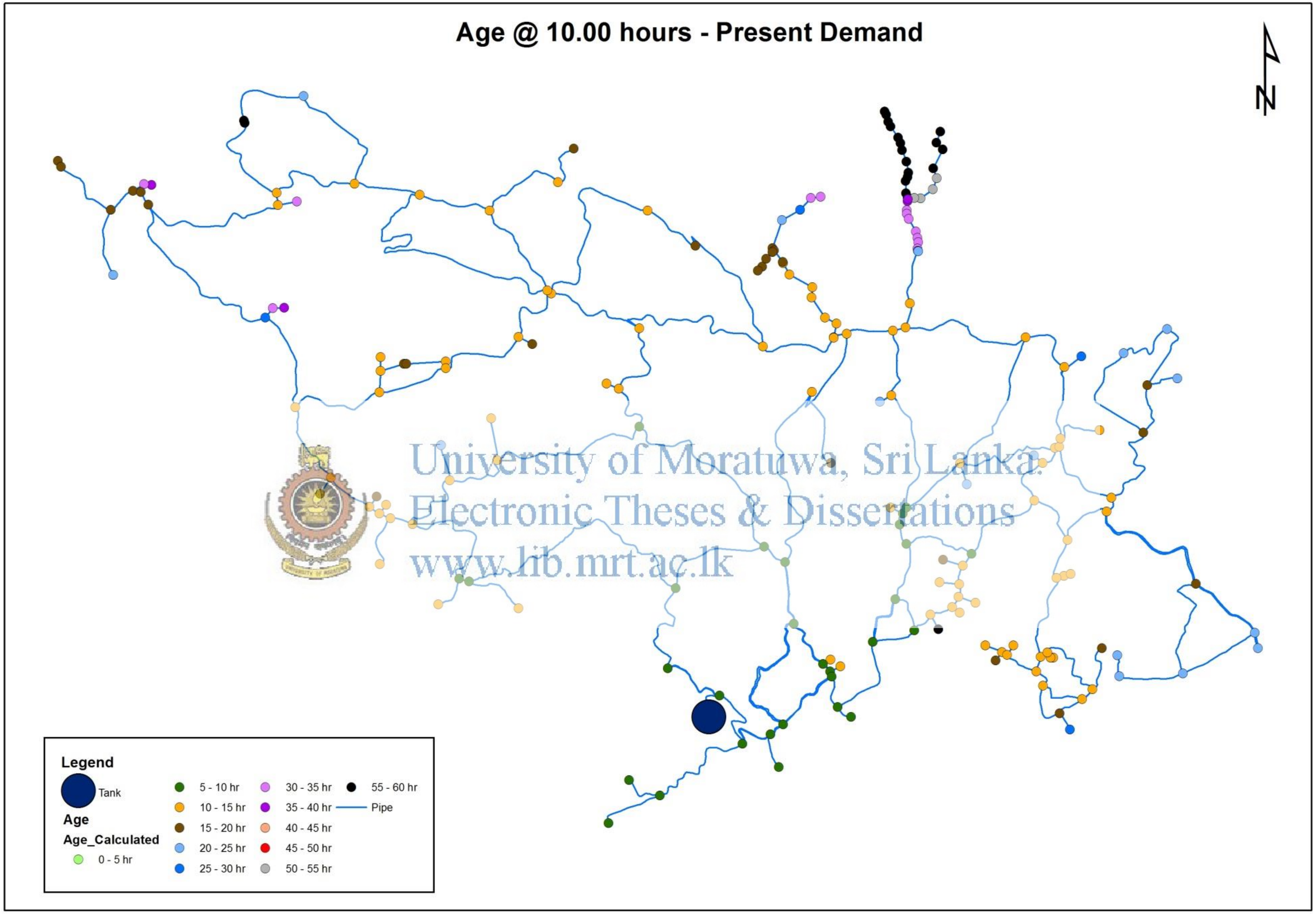


Figure 4.14: Water Ages of Maligathenna scheme at 1000 hours under present demand

System pressure data at 1000hrs is obtained through the hydraulic model. (Figure 4.13) Predicted pressure variation of the scheme under future demand is shown in figure 4.15. At present pressure values vary in a wide range due to rapid changes in the terrain. These values were compared with actual pressure values of the system, so the model is realistic. As per the guidelines on Level of Service specified by National Water Supply & Drainage Board, minimum pressure to be maintained throughout the pipeline distribution network is 1 bar to meet the expected demand of customers. Hence the Maligathenna scheme conforms that requirement. If the system pressure drops below 1 bar there can be a health hazard since the pressure in the pipes keeps contaminated water from entering the system. When pressure in a pipe is too low or is negative, contaminants from nearby ditches, cross-connections, and poor quality house plumbing can be drawn into the water system.

The maximum pressure is determined according to the Type of PVC pipes used. Maximum allowable pressure for type 600 pipes is 4.8 bars and maximum allowable pressure for type 1000 pipes is 8 bars with the provision to allow fire flow. Compared to those values there is a risk of pipe bursts in several locations in the distribution system and further could receive customer complaints on their fittings and plumbing accessory damages. There is a very high pressure value of 8.98 bars near Kadugannawa town which is comparatively a low elevated area, leaving the system and customers in a high risk environment. As a remedial action break pressure tanks could be setup appropriately.

Water age values scatter 1 hour to 26 hours in this pipe distribution system. (figure 4.14) Extreme ends of the system and low population density areas are highly vulnerable to have higher water ages. However with the increasing demand in the future, age decreases. (Figure 4.17) Water age is a hydraulic parameter and depends primarily on water demand, system operation and system design. Water age is significantly affected by storages, excessive capacities in the distribution system to meet emergency requirement and low demands during initial period of design. Thus the age should be controlled by system design and system usage.

Water age is a major factor in water quality deterioration within the distribution system. The two main mechanisms for water quality deterioration are interactions between the pipe wall and the water and reactions within the bulk water itself. As the bulk water travels through the distribution system, it undergoes various chemical, physical and aesthetic transformations, impacting water quality. Depending on the water flow rate, finished water quality, pipe materials and deposited materials (sand, iron, manganese) these transformations will proceed to a greater or lesser extent.

In order to eliminate the above mentioned unfavorable situations it is necessary to bring down the system water age as lower as possible. Then there will not be sufficient time to instigate above mentioned reactions in water. For the intention of bringing down the water age, there are several initiatives that could be implemented as remedial actions to optimize the system water age values. This could be done either by adding new pipelines to the system or by changing diameters appropriately. However both initiatives should be implemented without compromising the pressure requirements of the system.

Adding new pipelines were not reasonable in this scheme because the area is totally covered by laying pipelines in almost all the potential roads. In addition it is not economical to add extra pipelines instead of having one pipeline. Therefore that aspect was omitted and further studies were carried out on optimizing the diameters to bring down the water age. As a trial the diameters of all pipes were reduced by one step except 63mm diameter pipes and the model was run under the present demand. Pipes which are having a high head loss (>5m/1000m) were not changed. The resulting model showed a significant decrease in water age in certain areas of the system. (Figure 4.15) Water age of more than 80% of the concerned nodes was in the range of 5hours to 15hours. Age of some nodes was still remaining unchanged because those points are very remote and high elevated areas having a very low water demand. However this outcome is not practically applicable at this moment to the existing system because it is not economical to implement. Therefore this kind of an analysis is very important to be carried out during the design stage of a scheme, because after implementation of the scheme it is not possible to change the pipe diameters. Else it will be very costly to make any changes to the system.

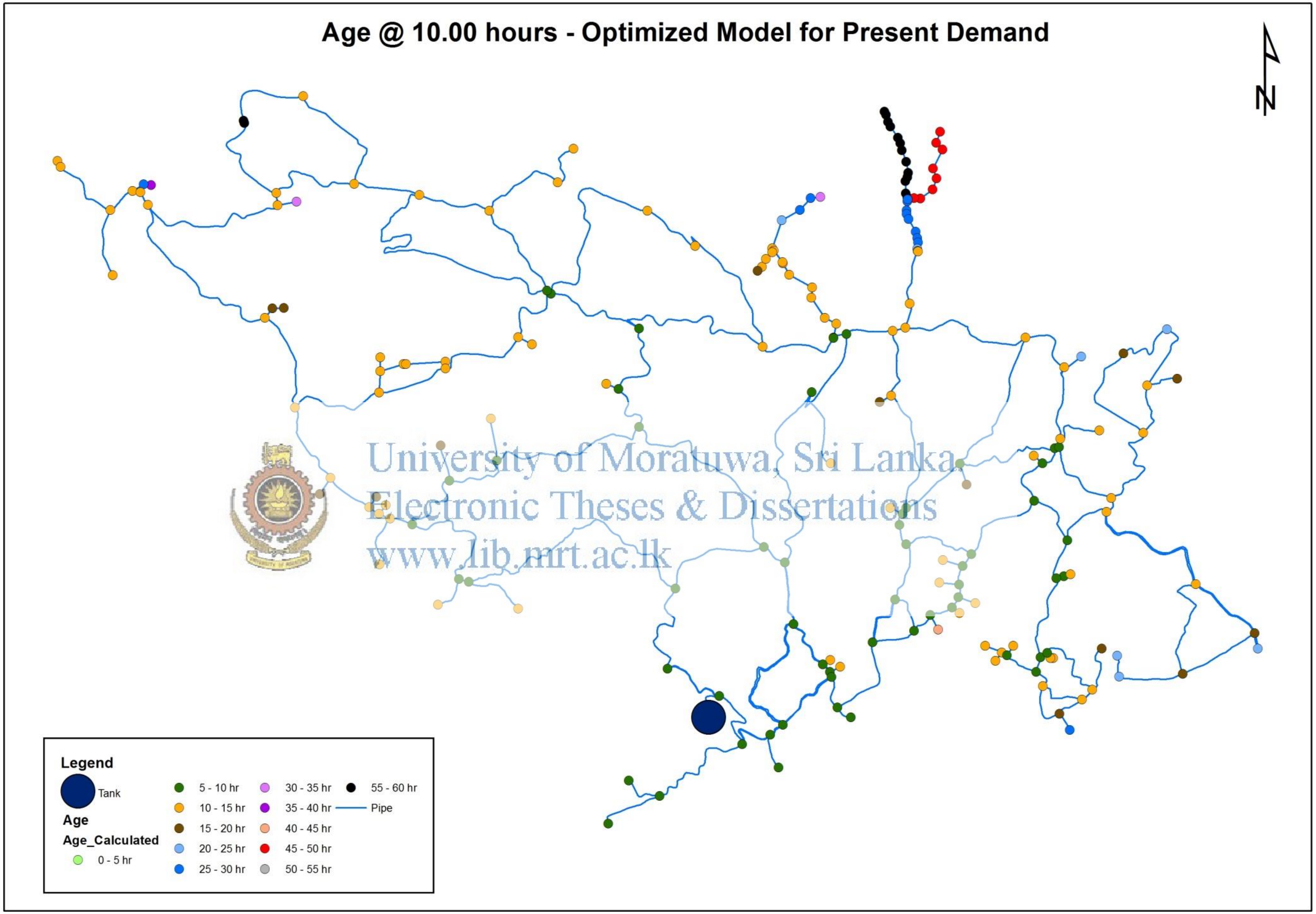


Figure 4.15: Water Ages of Maligathenna scheme at 1000 hours under present demand – Optimized Model

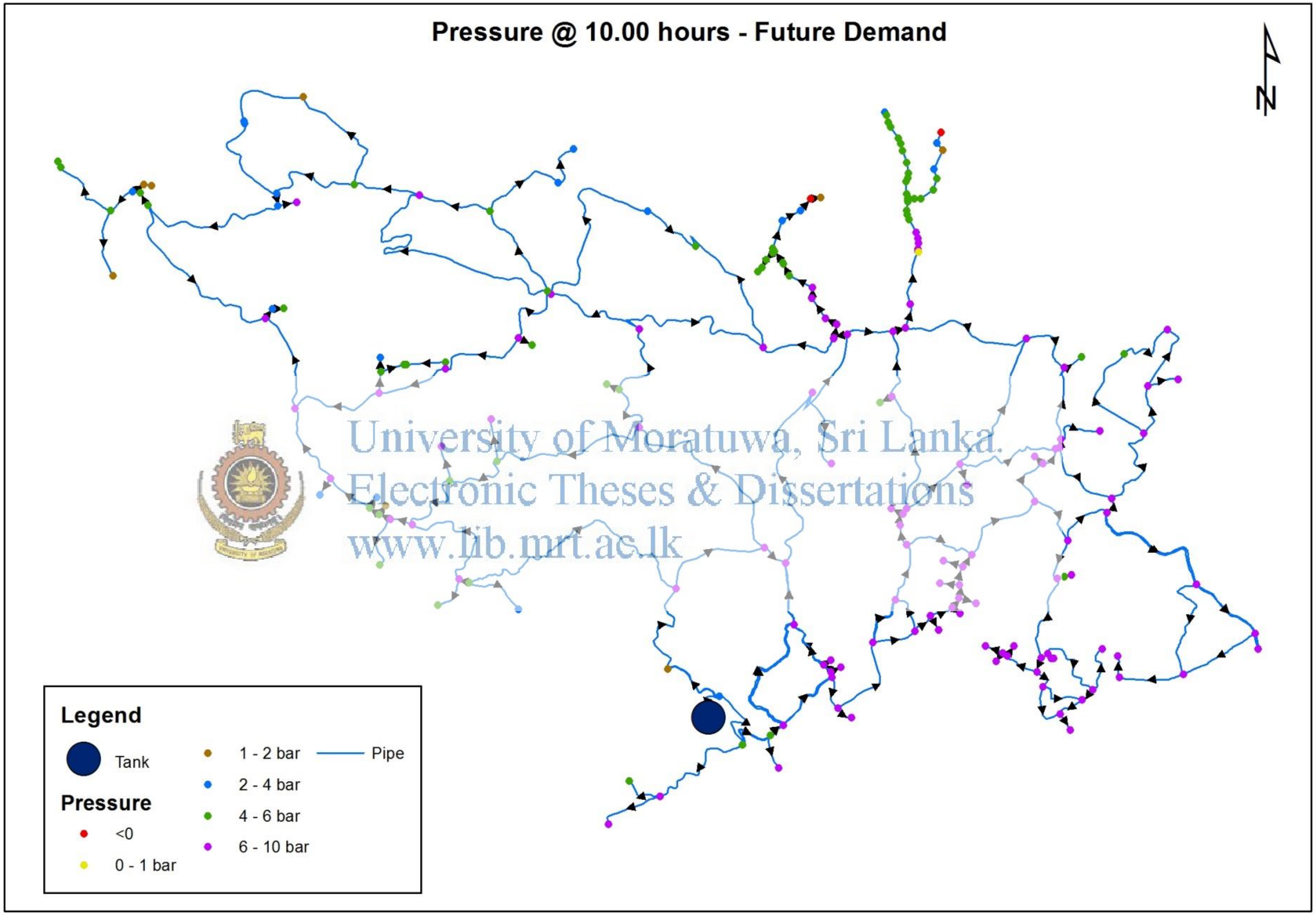


Figure 4.16: Pressure variation of Maligathenna Scheme under future demand

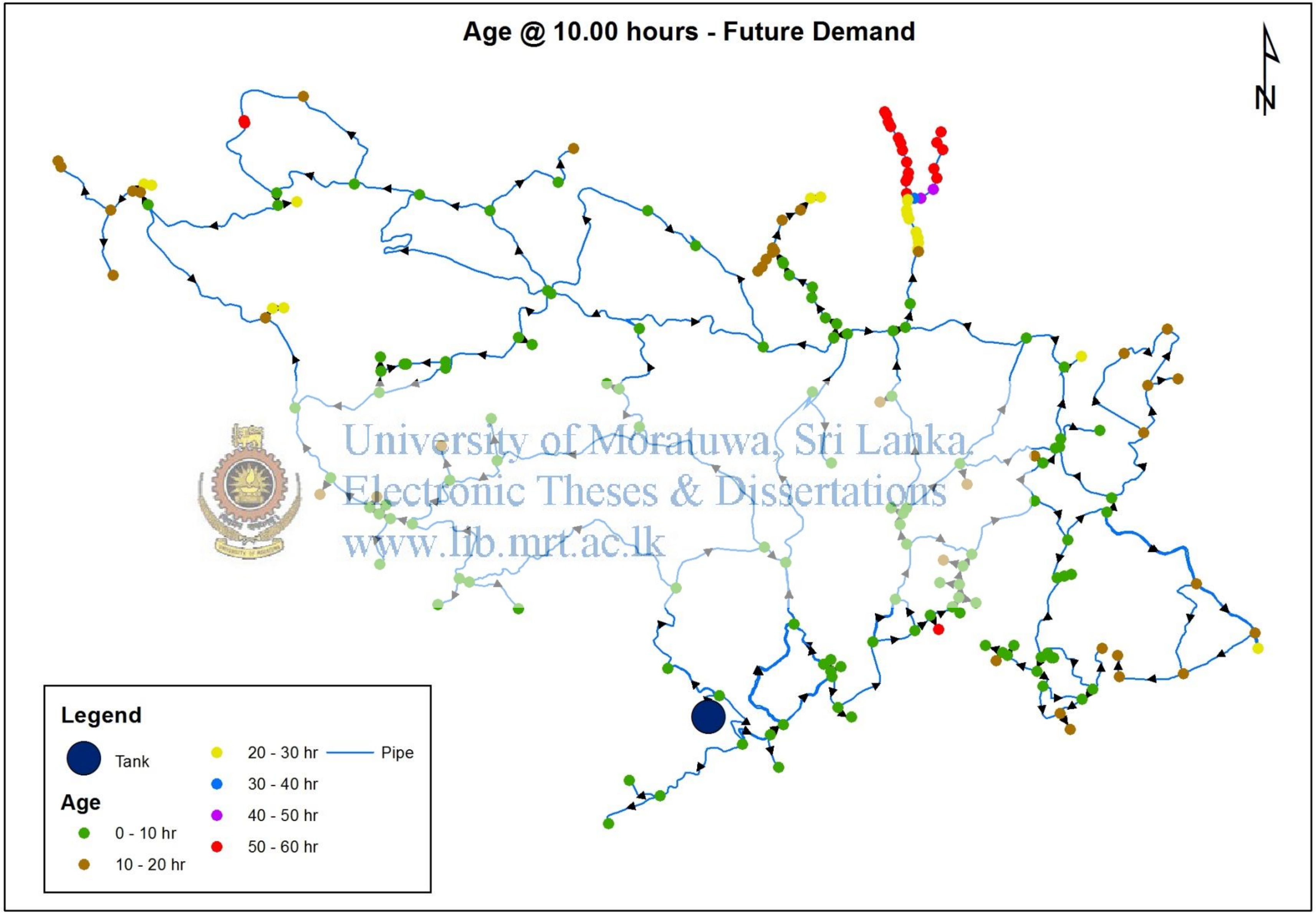


Figure 4.17: Age variation of Maligathenna Scheme under future demand

4.3.5 TTHM and RCl data comparison of Kandy South region reservoirs

Table 4.8: Water quality comparison of reservoirs

Reservoir Name	Capacity m^3	MSL	No of connections	Capacity per Connection	RCl mg/l	TTHM ppb
Augusta Watta	450	623.00	1255	0.36	0.10	54.847
Eriyagama	860	542.70	2618	0.33	0.00	26.388
Bowalawatta	820	740.30	1195	0.69	0.20	41.581
Prospect Hill	1140	585.70	1864	0.61	0.20	16.520
Kendakaduwa	294	545.48	617	0.48	0.20	16.254
Lagamuwa	600	630.73	1520	0.39	0.10	57.059
Madarangoda	593	558.90	1981	0.30	0.10	30.577
Mahakanda	172	543.38	407	0.42	0.60	23.668
Mobrey 02	300	713.00	470	0.64	0.50	23.668
Panabokka	536	655.37	747	0.72	0.10	48.581
Karuwalawatta	800	654.00	2221	0.36	0.20	41.733
Angunawala	1700	587.82	7269	0.23	0.10	23.242
Mobrey 01	425	619.60	131	3.24	N/A	N/A
Kehelwala	1100	612.93	3989	0.28	0.15	31.279
Maligathenna	356	594.84	3702	0.10	0.15	48.899

N/A – Not available

Summary of water quality data is given in the above table 4.7. All most all the reservoirs were having significantly high TTHM values with respect to the worldwide standards. RCl values were satisfactory only in 6 reservoirs out of 14 reservoirs investigated. The formation of TTHM and deterioration of RCl were supposed to be due to the high retention times in reservoirs. Capacities of these reservoirs were determined based on the future demand of the region; hence the system is running under capacity at present. Consequently an undue retention time could be expected in the system. In order to assess the retention time of reservoirs a new parameter was introduced which is the proportion between the capacity of reservoir and number of connections served from that particular reservoir. There it was observed that TTHM concentration was having a reasonable degree of correlation with that parameter. Hence there is a possibility of THM formation when the reservoirs are operating under capacity. As shown in figure 4.18 THM formation decreases with the capacity per connection up to a certain level and starts to increase thereafter. In addition there could be a relationship between the reservoir turbidity level and THM formation. Unfortunately at present turbidity data of each reservoir is not available for the analysis. The study could be further continued by analyzing that aspect in future.

However there is a trend to increase the pH in concrete tanks due to excessive detention time. Other possible means of contamination of drinking water in reservoirs include intrusion of sediments, small animals or insects through faults such as damage to roofs, including gaps in hatches and covers, gaps between the roof structure and the tank wall, cracks in concrete tank walls or corrosion of metal parts, gaps at entry points of pipework or cables etc.

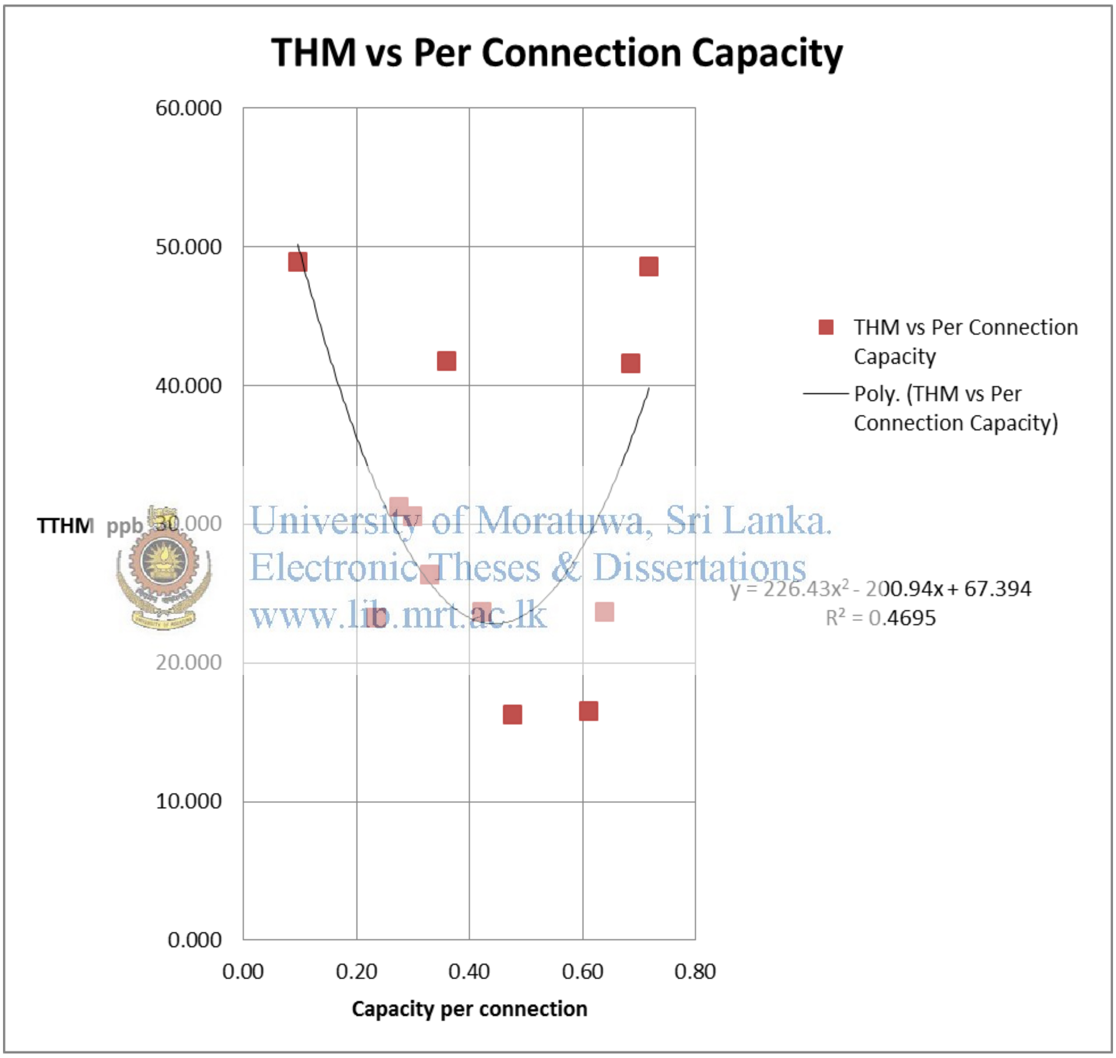


Figure 4.18: Graph of TTHM vs Per connection capacity

A detailed age analysis was carried out for Maligathenna reservoir to identify possible extremes of water age. Following figure 4.19 and figure 4.20 show the age variation for both present demand and future demand. Under present demand maximum age observed is around 9.5 hours. With the increased demand in future, age goes down to a maximum of 4.25 hours. Therefore this issue is associated with the under capacity situation of the scheme. This type of analysis could be carried out to all the 15 reservoirs in the region and check the worst retention time and the associated risks. In addition a suitable end customer survey could be carried out to check the domestic water retention time in their domestic water tanks and the water quality.

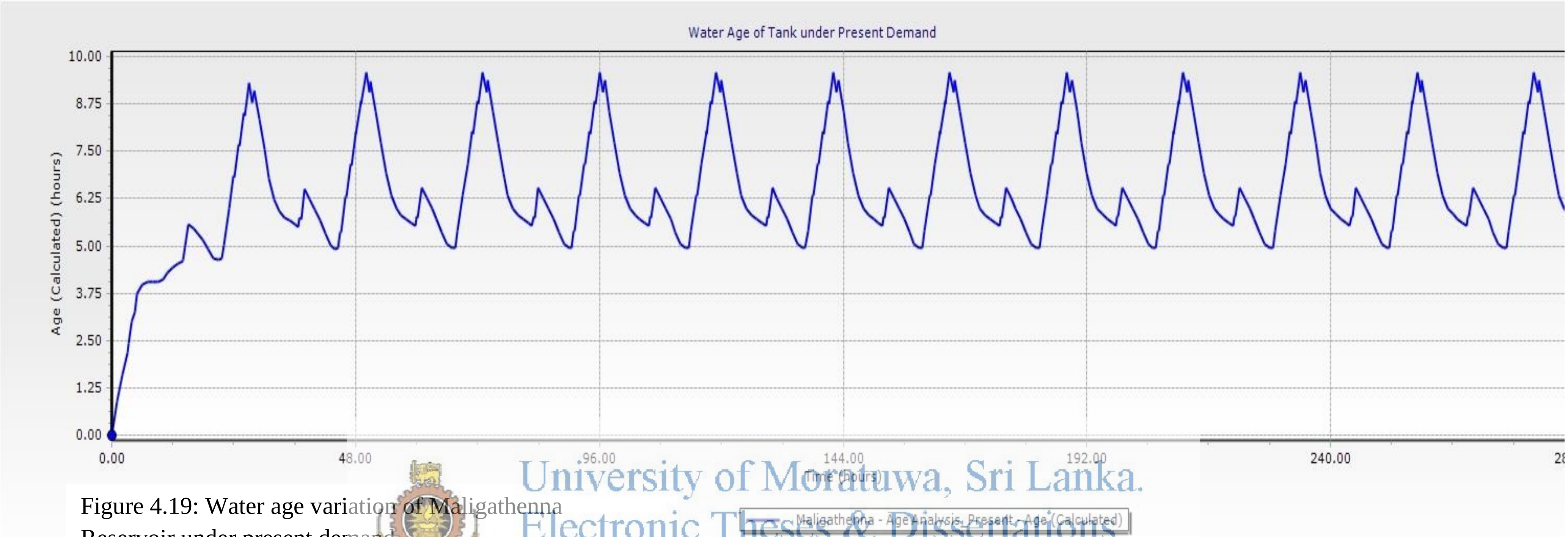


Figure 4.19: Water age variation of Maligathenna Reservoir under present demand

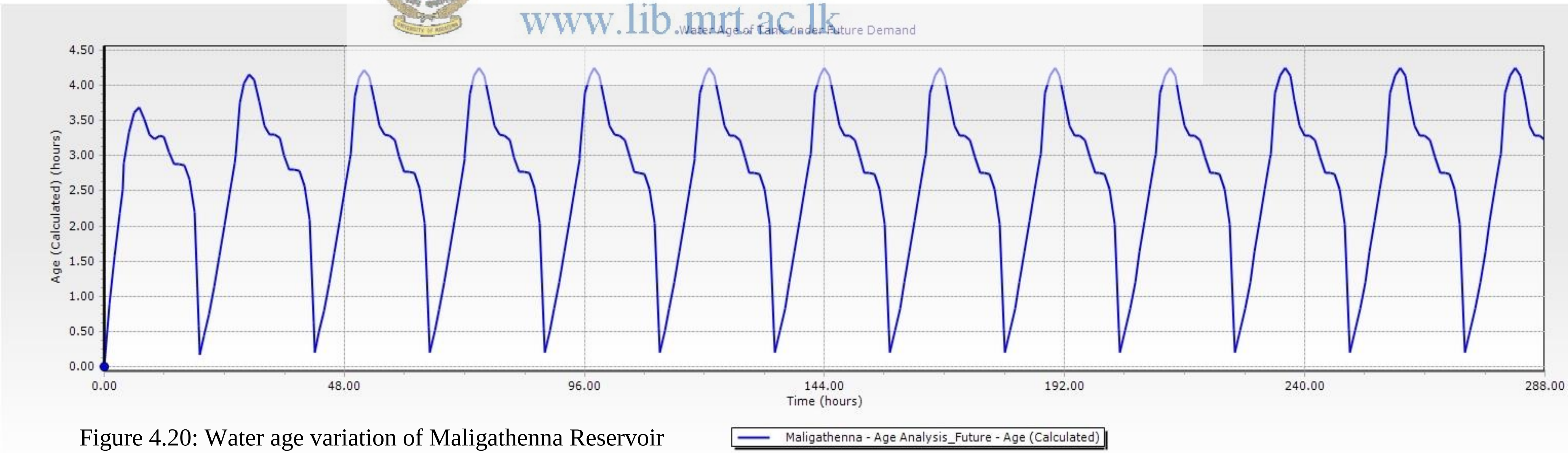


Figure 4.20: Water age variation of Maligathenna Reservoir under future demand

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research study was carried out based on the main objective of using WSP concepts to risk mitigation in Maligathenna Water distribution system. Accordingly Maligathenna scheme was critically analyzed, probable risks which were not properly focused before were identified and their occurrence was assessed. Subsequently following conclusions were made based on those observations and findings.

1. Residual chlorine level is regarded as an indicator for microbiological safety of drinking water, since the measurement is much more convenient, cheaper and quick compared to microbiological examination. Considering the measured residual chlorine levels, the system was found to be highly vulnerable for microbiological contamination. In addition to the in-situ RCl measurements, a properly calibrated water quality model could be used to estimate the RCl values of the system. The accuracy of the model highly dependent on the values of input parameters and level of calibration. Maintaining the RCl value of 0.2mg/l is difficult throughout the system by current chlorination techniques. Maintaining a very high RCl value at the treatment plant is also not advisable with respect to the health of consumers and aesthetics. When the system gets saturated by the end of design horizon, this problem will be alleviated. However the laboratory data on microbiological parameters carried out by Greater Kandy regional laboratory do not highlight any contaminated situation in the system, hence there is a suspicion on the accuracy level of either RCl data or regional laboratory data. Further studies are recommended to reach more reliable conclusions.
2. Though it is not much highlighted by NWSDB, there is a risk of THM in the water distribution system. The contamination level is significantly high compared to developed countries. There is a possibility of a positive relationship between RCl and THM. In certain sampling locations, the THM formation may be induced by the high level of TOC because TOC level is above 2mg/l. Turbidity and conductivity levels are quite satisfactory in this system.

3. The hydraulic modelling showed that there are several high pressure zones in the system that need to be focused on. It is a risk for the pipelines and specials (Valves, flow meters etc.) as well as for the consumers. Those segments should be rectified in order to avoid the possible pipe bursts and customer complaints. Water stagnation also needed to be addressed, especially during the design stage, because there are certain areas in the scheme having very high water age which could lead to contamination. A properly calibrated water quality model could be used to determine the water age of any segment of the pipe distribution system. It is not economical to adjust the pipelines after the construction phase to address the aging problem.
4. Both water quality and hydraulic data were critically analyzed to find out a linear, polynomial or logarithmic inter-relationship among them. Unfortunately any significant relationship was not found other than a few poor correlations. The reasons behind this situation could be the inadequate data and the unreliability of the analyzed data. It could be concluded that the trend line method in MS excel is not suitable for this type of analysis, further advanced method should be used for better results.
5. Results showed that the service reservoirs in the Kandy South region are having significant THM levels; as a result the entire pipe network is vulnerable for THM contamination. The reason may be that the system demand is still in the before saturation stage, therefore reservoirs are having over capacities under the present demand resulting the water is unnecessarily stagnated in the reservoirs. This is also a problem that should be considered during the design stage of the scheme. As such the system hydraulics and system water quality should be accommodated simultaneously during the design stage.

5.2 Recommendations

1. Proper initial studies should be carried out to decide the actual demand of the population and the growth pattern during the pre-feasibility stage. The chlorination system and the reservoir capacities of a scheme shall be designed based on two scenarios such as less than design capacity and full capacity

consumption. Booster chlorination will be a practical solution to handle issues during the before saturation period. Reservoir retention time could be reduced by compartmentalizing the reservoir to cater the partial demand.

2. Decentralized small scale treatment facilities should be encouraged rather than constructing large scale treatment plants. So that the monitoring is more effective.
3. During the design stage of a water distribution system, water quality aspects (water age, residual chlorine etc.) also should be addressed simultaneously with the hydraulic analysis. Dead ends should be avoided as much as possible; instead ring type systems could be introduced.
4. Advanced studies should be carried out on THM variation patterns and risk factors in NWSDB schemes and do the needful to eliminate the risk. If excessive organics are the problem, treatment techniques should be changed. (Eg: coagulation, magnetic ion exchange etc.) If chlorination is a main precursor alternative disinfection method such as chloramination could be adopted. If water age matters, turnover of storage tank could be increased by dropping the high water level or taking the reservoir out of service during the low flows.

5. Proper technical control measures should be carried out regularly at operational and maintenance level as follows.
    - Regular line flushing
    - Leak detection programs
    - Provide continuous supply
    - Water quality surveillance
    - Regular checking the condition of specials (Valves, flow meters etc.)
6. Water quality and hydraulic parameter contours could be used to predict the system properties. A suitable interpolation technique should be used to build the contours.
7. The excessive pressure in pipelines could be managed by installing break pressure tanks in suitable locations. Zonation valves could be introduced to the system to control the age, pressure as well as contamination during a pipe burst.

8. The new parameter introduced to assess the water stagnation in reservoirs "Capacity per connection" could be further modified to achieve a more realistic figure.
9. Artificial neural network method is the ideal method that could be used to investigate the co-relations between two variable parameters while other variable parameters could be kept constant.
10. Implementation of water safety plan in distribution system will bring all these relevant issues in to discussion and suitable remedial actions could be formulated.

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APPENDICES

Appendix A – Determination of THM in drinking water by Headspace technique with capillary column Gas- Chromatography (Kuivinen and Johnsson, 1998 headspace method)

A simple and rapid headspace method for gas chromatographic determination is used to determine trihalomethanes in drinking water. The quantification is based upon the internal standard 1,1,2-trichloroethane, which elutes in the middle of the chromatogram. The relative standard deviations for most of the substances are between 0.8-8% for concentrations of 1 and 50 mg/l, respectively. The limits of quantification (LOQ) are <0.1 mg/l for three of the THM analytes and 0.2 mg/l for bromoform. The chlorinated solvents have LOQ<0.1 mg/l except dichloromethane which has 2 mg/l. The analytes show linear ranges up to 75 mg/l. The results of THM from the survey of 209 Swedish drinking water samples showed that 3% exceeded the Swedish limit value of 50 mg/l of total THM.

This is an easy and relatively fast and inexpensive alternative to the conventional liquid-liquid extraction method for the determination of highly volatile halogenated hydrocarbons in drinking water. The consumption of organic solvents has been reduced to a minimum which involves environmental as well as economic advantages for the method. The assay was linear within the concentration range of the method which includes most of the samples from the investigation of the drinking water from the Swedish waterworks. The results from the Swedish drinking water are relatively low compared with many other countries but there are several samples which exceeded the guide level and even some exceeded the limit value. The reason for this could be a mistake in the chlorination procedure. The critical step is supposed to be the balance between organic material in the surface water and the addition of an appropriate amount of the chlorination agent, which has to be recalculated from time to time.

Appendix B - Model Calibration as illustrated in WaterGEMS V8i Help

Calibration is the process of comparing the model results to field observations and, if necessary, adjusting the data describing the system until model-predicted performance reasonably agrees with measured system performance over a wide range of operating conditions. The process of calibration may include changing system demands, fine tuning the roughness of pipes, altering pump operating characteristics, and adjusting other model attributes that affect simulation results. There are two types of calibration methods.

- Static methods (Used with steady-state model)
- Dynamic Methods (Used with EPS Model)

As per the WaterGEMS V8i Help calibration criteria is as follows

- Fitness Type - Select the Fitness Type you want to use from the drop down list. In general, regardless of the fitness type you select, a lower fitness indicates better calibration. Fitness Types include: Minimize Difference Squares, Minimize Difference Absolute Values, and Minimize Maximum Difference.

- Minimize Difference Squares - Uses a calibration designed to minimize the sum of squares of the discrepancy between the observed data and the model simulated values (Model simulated values include hydraulic grades and pipe discharges). This calibration favors solutions that minimize the overall sum of the squares of discrepancies between observed and simulated data.

- Min. Diff. Absolute Values - Uses a calibration designed to minimize the sum of absolute discrepancy between the observed data and the model simulated values. This calibration favors solutions that minimize the overall sum of discrepancies between observed and simulated data.

- Minimize Max. Difference - Uses a calibration designed to minimize the maximum of all the discrepancies between the observed data and the model simulated values. This calibration favors solutions that minimize the worst single discrepancy between observed and simulated data. Note that the Minimize

Maximum Difference Fitness Type is more sensitive to the accuracy of data than other Fitness Types.

- Head/Flow per Fitness Point - Head and Flow per Fitness Type provide a way for you to weigh the importance of head and flow in your calibration. Set these values such that the head and flow have unit equivalence. You can give higher importance to Head or Flow by setting a smaller number for its Per Fitness Point Value.

- Flow Weight Type - Select the type of weight used: None, Linear, Square, Square Root, and Log. The weighting type you use can provide a greater or lesser fitness penalty.

Acceptable Levels of Calibration

Each application of a model is unique, and thus it is impossible to derive a single set of guidelines to evaluate calibration. The guidelines presented below give some numerical guidelines for calibration accuracy; however, they are in no way meant to be definitive. A range of values is given for most of the guidelines to reflect the differences among water systems and the needs of model users. The higher numbers generally correspond to larger, more complicated systems, and the lower end of the range is more relevant to smaller, simpler systems. The words "to the accuracy of elevation and pressure data" mean that the model should be as good as the field data. If the Hydraulic Grade Line (HGL) is known to within 2.5 m, then the model should agree with field data to within the same tolerance. It is important to remember that these guidelines need to be tempered by site specific considerations and an understanding of the intended use of the model (Walski et al., 2003).

- Master planning for smaller systems [24-in.(600-mm)pipe and smaller]: The model should accurately predict hydraulic grade line(HGL) to within 5-10ft(1.5–3 m) (depending on size of system) at calibration data points during fire flow tests and to the accuracy of the elevation and pressure data during normal demands. It should also reproduce tank water level fluctuations to within 3–6 ft

(1–2 m) for EPS runs and match treatment plant/pump station/ well flows to within 10–20 percent.

- Master planning for larger systems [24-in.(600-mm)and larger]: The model should accurately predict HGL to within 5–10 ft (1.5–3 m) during times of peak velocities and to the accuracy of the elevation and pressure data during normal demands. It should also reproduce tank water level fluctuations to within 3 to 6 ft (1–2 m) for EPS runs and match treatment plant/ well/pump station flows to within 10–20 percent.

- Pipeline sizing: The model should accurately predict HGL to within 5–10 ft(1.5–3 m) at the terminal point of the proposed pipe for fire flow conditions, and to the accuracy of the elevation data during normal demands. If the new pipe impacts the operation of a water tank, the model should also reproduce the fluctuation of the tank to within 3–6 ft (1–2 m).

- Fire flow analysis: The model should accurately predict static and residual HGL to within 5–10 ft (1.5–3 m) at representative points in each pressure zone and neighborhood during fire flow conditions and to the accuracy of the elevation data during normal demands. If fire flow is near maximum fire flow such that storage tank sizing is important, the model should also predict tank water level fluctuation to within 3–6 ft (1–2 m).

- Subdivision design: The model should reproduce HGL to within 5–10 ft(1.5–3 m) at the tie-in point for the subdivision during fire flow tests and to the accuracy of the elevation data during normal demands.

- Rural water system (no fire protection): The model should reproduce HGL to within 10–20 ft (3–6 m) at remote points in the system during peak demand conditions and to the accuracy of the elevation data during normal demands.

- Distribution system rehabilitation study: The model should reproduce static and residual HGL in the area being studied to within 5–10 ft (1.5–3 m) during fire hydrant flow tests and to the accuracy of the elevation data during normal demands.

- Flushing: The model should reproduce the actual discharge from fire hydrants or distribution capability [such as the fire flow delivered at a 20 psi(138 kPa) residual pressure] to within 10–20 percent of observed flow.

- Energy use: The model should reproduce total energy use over a 24-hour period to within 5–10 percent, energy consumption on an hourly basis to within 10–20 percent, and peak energy demand to within 5–10 percent.

- Operational problems: The model should reproduce problems occurring in the system such that the model can be used for decision-making for that particular problem.

- Emergency planning: The model should reproduce HGL to within 10–20 ft(3–6m) during situations corresponding to emergencies (for example, fire flow, power outage, or pipe out of service).

- Disinfectant models: The model should reproduce the pattern of observed disinfectant concentrations over the time samples were taken to an average error of roughly 0.1 to 0.2 mg/l, depending on the complexity of the system.